Ship emission study based on Automatic Identification System (AIS) data

Treball Final de Grau

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Thanking you

Xavier Calvo Surià

Resum

Aquest projecte de fi de grau pretén utilitzar dades del Sistema d'Identificació Automàtica (AIS) per a calcular les emissions produïdes per rutes regulars de vaixells en el Mediterrani. La recerca ha estat desenvolupada utilitzant el software SIMROUTE, el qual ha estat produït a la Universitat Politècnica de Catalunya i permet obtenir rutes òptimes i les seves emissions basant-se en factors afegits. El treball pretén implementar l'ús de les rutes AIS i, en conjunt amb informació de vaixells reals i una agrupació de les metodologies de STEAM i EMEP, ser capaç d'obtenir aproximacions del consum i les emissions anuals dels vaixells. Com a resultat, s'obtenen una sèrie d'eines que permeten agrupar arxius AIS en paquets i calcular el consum de combustible i les emissions de manera ràpida i senzilla. A més a més, un programa que permet la representació d'aquests paràmetres en el seu consum o generació horaris, i unes guies per tal de fer accessibles les contribucions per nous estudis i recerques.

Abstract

This end of degree project aims to use data from the Automatic Identification System (AIS) to calculate the emissions produced by regular ship routes in the Mediterranean. The research has been developed using SIMROUTE software, which has been created at the Universitat Politècnica de Catalunya and obtains optimum routes and their emissions based on added factors. This work focuses on implementing the use of AIS routes, together with information of real vessels and a merged methodology of STEAM and EMEP methods for emission calculation and be able to obtain estimated annual fuel consumption and emission of pollutants. As a result, a series of modules have been created which will allow to group AIS files into packages and determine the consumption and emissions in a fast and easy way. In addition, another program which represents these parameters in their hourly rates, and a guide that will make these new additions available for other studies and researches.

Taula de continguts

Chapter 1. Introduction

1.1 Emissions, a global and local issue

Pollution has become a very important topic since reports have proved that not only it is the reason of climate change but also it endangers the health of humanity. The way to tackle this problem is in every aspect of society, and the easier way to start is locally. In January 2020, Barcelona's town hall (Ajuntament de Barcelona), published a press note [1] which stated that the global activities linked to the port and airport of Barcelona generate four times more CO_2 than the CO_2 generated in the actual city, assigning 5,332,522 tons of CO_2 to the annual activity of Barcelona's port. This created controversy with Port of Barcelona leaders, that denied [2] such given numbers and reduced them to an approximate of 315,000 tons of CO_2 generated annually by ship and port activities in Barcelona, later accusing the town hall that the calculation used had obtained the numbers from the calculation of the total emissions of ships (including their trips outside the area of Barcelona), and stating that their method of calculation was 'approved' by international experts.

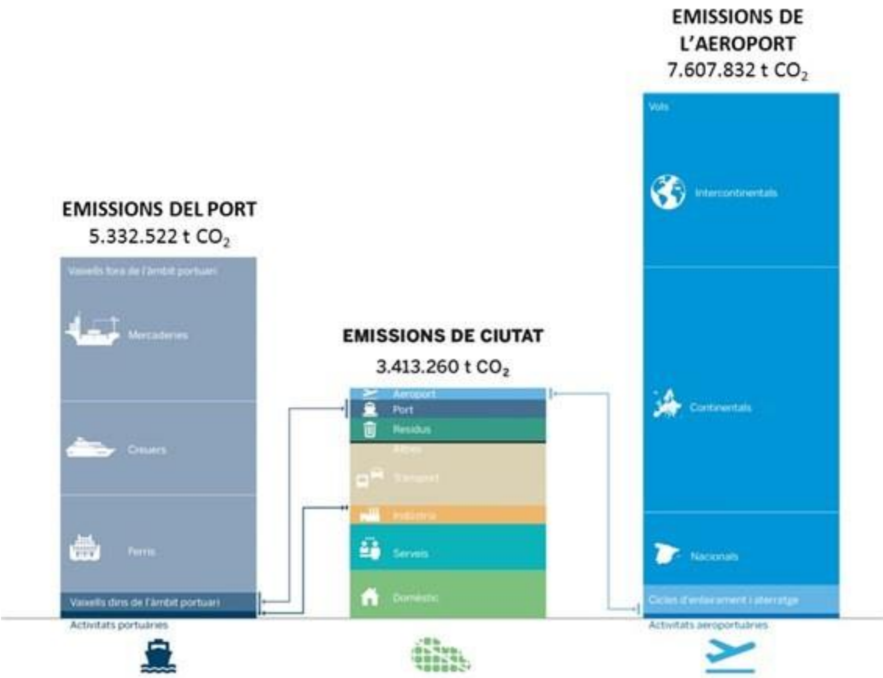


Figure 1 – Breakdown of the CO_2 emissions in Barcelona. It can be seen that according to Barcelona's town hall the port of Barcelona generated in one year 5,332,522 tonnes of CO_2. Source: [1]

Although there are new measures to be introduced by the town hall such as new ecotaxes, electrification of maritime transport and activities, the impulse of renewable energies, and others, the aim is to improve control and monitoring of emissions in these areas. That follows the approach of the European Union on emission monitoring plans.

As reported by [3], the maritime transport is a substantial CO_2 emitter with more than 138 million tonnes of CO_2 emitted in 2018, composing the 3% of the total EU emissions, comparable to the total of emissions of Belgium, and are likely to grow in the future. It also accounts for 44 million tonnes of fuels consumed, which were composed by 70% of heavy fuel oils (which is a residual fuel and a heavy pollutant), 20% of marine gas oil and diesel, and 3% of Liquefied Natural Gas (LNG). Other information published is regarding the most CO_2 emitters, with container ships in the first place with a 30% of the total emissions, followed by tankers (20%), Ro-Pax and Ro-Ro (15%) and bulkers (13%).

The Greenhouse gas pollutants regulated which are produced by shipping are CO_2, SO_x, and NO_x. Firstly, CO_2 has been found to contribute to global warming by trapping heat in the atmosphere, and negatively affecting ecosystems, included those marine areas by increasing the acidity of seawater. On second place, the emission of sulphur dioxides SO_x contribute to acid rain, with a negative and significant impact on health. Finally, nitrogen oxides (NO_x) are gases that cause the acidification and eutrophication (overgrowth of algae life) of water and soil, but also lead to the creation of particulate matter and ground-level ozone.

The European Commission declares [4] that 'shipping emissions represent around 13% of the overall EU greenhouse gas (GHG) emissions from the transport sector (2015).', and it sets out a strategy created in 2013 to be used to reduce GHG emissions from the shipping industry [6]:

- Monitoring, Reporting and Verification (MRV): which was adopted in 2015, introducing rules for the monitoring, reporting and verification of CO_2 emissions from maritime transport. 'Shipping companies have to report their annual CO_2 emissions and other relevant information arising from their ships' voyages to and from European Economic Area (EEA) ports, including CO_2 emissions from these ships in ports. This concerns ships above 5000 gross tonnage,' while 'smaller ships are excluded from the rules. The monitoring of fuel consumption, CO_2 emissions and energy efficiency started in 2018, and shipping companies had to submit their first emission reports in 2019.'
- Definition of reduction targets for the maritime transport sector: for EU international maritime transport, a reduction target of 40%-50% by 2050 compared to 2005.
- Application of a market based measure: that would put taxes related on emissions for the products sold in the European market, therefore, providing incentives to achieve emission reductions.

On a global scale, according to [5] 'maritime transport emits around 940 million tonnes of CO_2 annually and is responsible for about 2.5% of GHG emissions (3rd IMO GHG study).' And, following the adoption of the EU MRV Regulation, the IMO established in 2016 the IMO Data Collection System (DCS). 'The system requires owners of large ships (above 5000 gross tonnage) engaged in international shipping to report information on fuel consumption of their ships to the flag States of those ships. The flag States then report aggregated data to the IMO, which shall produce an annual summary report to the IMO Marine Environment Protection Committee (MEPC).' This system started officially in March 2018 and the collection of data started on 1 January 2019. Consequently, ships calling in the EEA zone have to report under the two regulations and in February 2019, the European Commission made a proposal of amendments to the EU regulations so that it streamlined and reduced the administrative effort for the companies and administrations as far as possible.

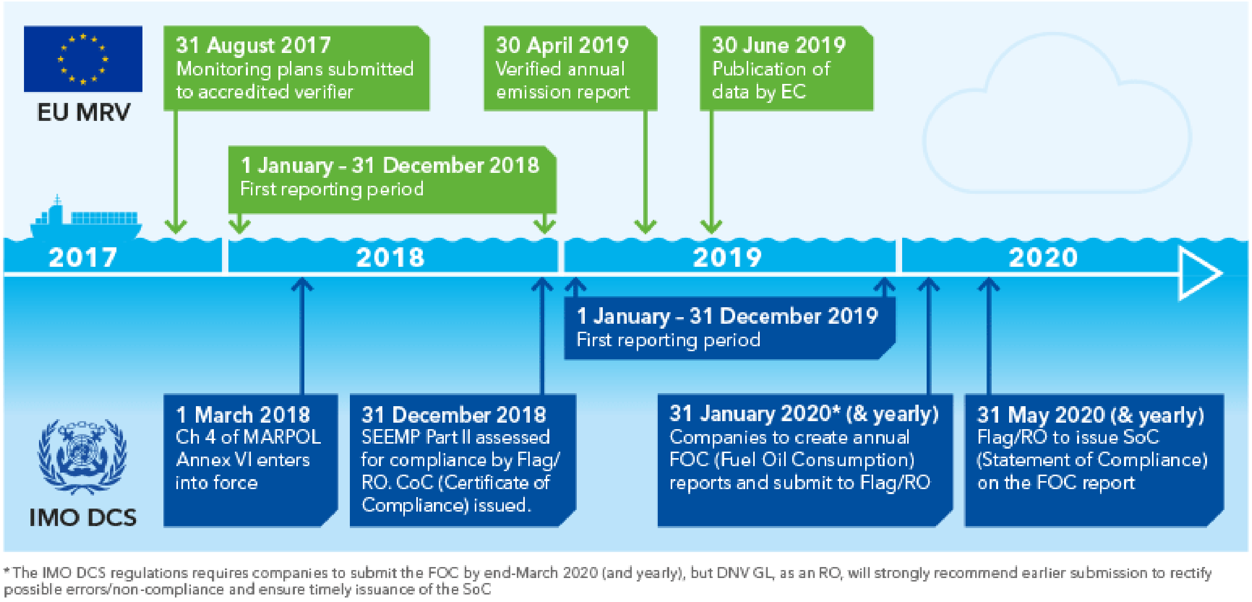


Figure 2 – Timeline of the implementation of EU MRV and IMO DCS. Source: [7]

It is important to point out that CO_2 emissions are not the only emissions that have been regulated. MARPOL's Annex VI [8], adopted in 1997, limits for the main air pollutants produced in ships exhaust gases, sulphur oxides (SO_x), and nitrogen oxides (NO_x), prohibited the deliberate emissions of ozone depleting substances (ODS), and also regulated the incineration of volatile organic compounds (VOC) from tankers. MEPC 58 adopted a revised MARPOL Annex VI in October 2008 with an associated NO_x Technical Code 2008, which entered into force on 1 July 2010. The main changes to MARPOL were a progressive reduction in global emissions of SO_x, NO_x and particulate matter, and the introduction of emission control areas (ECAs) to reduce emissions of these in designated sea areas. (Which is one of the new measures to be supported by Barcelona's town hall, to introduce a Mediterranean MED-ECA in order to protect the marine ecosystem and coastal regions from ship emissions).

Returning to emission monitoring from shipping activities, the European Monitoring and Evaluation Programme (EMEP) / European Environment Agency (EEA) or to shorten it EMEP/EEA provides with an air pollutant emission inventory guidebook [9] which has been designed to facilitate reporting of emission inventories to the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution and the EU National Emission Ceilings Directive. This guidebook lays out several methods for the estimation of emissions from navigation depending on the availability of data. Starting from a Tier 1 and Tier 2, they approach the estimation by using fuel sales as the primary activity indicator, and also assuming average vessel emission characteristics. On the other hand, a Tier 3 is regarded as the ship movement methodology and is based on ship movement information for individual ships.

According to [9], the ship movement methodology is recommended when detailed ship movement data as well as technical information on the ship (e.g. engine size and technology, power installed or fuel use, hours in different activities) are available. It is suited for estimating national and international emissions. However, the methodology may be quite time consuming to perform'.

From the MRV implementation point of view, there are several Emission Calculation Methodologies (ECM) considered in [10] that can be chosen by shipping companies to define their monitoring plan.

More specifically, eleven methods for fuel consumption and emission determination were studied: ENTEC UK Limited; Ship Traffic Emissions Assessment Model and latest versions (STEAM); methods for estimating shipping emissions in the Netherlands; the California Air Resources Board (CARB) method; Use of questionnaires method; On board monitoring devices; Use of Portable Emission Measurement Systems (PEMS); Flow meters for applicable combustion processes; Continuous Emission Measurements (CEM); Bunker fuel tank monitoring; and Bunker Fuel Delivery Note.

For instance, STEAM evaluates exhaust gas emissions of marine traffic using the messages provided by the Automatic Identification System (AIS), and at the same time positioning the emissions with high spatial resolution. There is also technical data considered for each individual vessel, and the latest update of the model comprises NO_x, SO_x, and CO_2 emissions, mass-based emissions of particulate matter (PM) and carbon monoxide (CO).

[10] also suggested that the STEAM methodology could be used to perform monitoring via modelling and, thus, monitoring would be performed from ship to shore and ship owners would only have to verify the results obtained. It also concluded, that this method has the potential to be have the most realistic outputs when comparing with real data.

1.2 Objectives

This project has been motivated by the need to provide tools for the study of the monitoring and verification of emissions. The paper will present new modules added to a software created at Universitat Politécnica de Catalunya (UPC) which is called SIMROUTE. These new features will allow for the calculation of fuel oil consumption and the emission of pollutant from real cases of ships.

Consequently, by combining EMEP/EEA's tier 3 methodology, STEAM methodology, and SIMROUTE emission software with AIS implementation, the main objective is to develop a set of tools to carry out the emission calculation of a real trip. This tool will be also used to carry out a case study using Tier 3 calculation.

In addition, the specific objectives are:

- To introduce emission calculation capabilities for real cases in SIMROUTE using Automatic Identification System (AIS) data.
- To validate the emission module designed with real fuel consumption results.
- To create a tool to put together a number of AIS routes and group them in months of the year.
- To create a tool to visualize the rate of emission and evaluate the behaviour of the ship.
- To carry out a case study in order to evaluate the introduced tools.
- To provide with a short and easy guide for the use of the new modules, and make the tools available for other researchers and students.

In this document, firstly there is an introduction to ship routing software and the state-of-the-art situation of the SIMROUTE software. Secondly, it is followed by a summary of the relevant regulations regarding the monitoring and emission limits of ships. Thirdly, there is a presentation of the emission calculation methods in which this project has been inspired, and a proposition of a method implemented into SIMROUTE. Fourthly, a case study is carried out to validate and evaluate the potential and limitations of this methodology, its results will be presented in tables and figures and later discussed in Chapter 4. Finally, the dissertation is concluded with some recommendations for future projects and a concise evaluation of the finished work.

1.3 State-of-the-art

1.3.1 SIMROUTE Ship Weather Routing Software

'Ship weather routing' is defined by the International Maritime Organization (IMO) [11] as the type of ship routing that provides navigators with 'optimum routes' to avoid bad weather. That is to propose safe and efficient routes and, at the same time, consider weather thresholds or the nature of the cargo. However, one of the main things that ship routing is trying to improve is fuel efficiency. According to Vessel Performance Optimisation Magazine, (VPO), [12] 'weather, including currents, waves, wind, and swell has been found to affect the performance of a vessel by between 50 and 80 per cent and cost thousands of euros in additional fuel consumption.' The constant necessity to improve energy efficiency, economic feasibility, and safety, while also complying with emission regulations, is a big motivation for on-going developments and improvements.

Ship routing uses pathfinding to optimize routes, which is defined at [13] as 'the plotting by a computer application, of the shortest route between two points.' There are, currently, multiple algorithms available such as the Bellman-Ford algorithm [15], the Dijkstra algorithm [16] and the A* Algorithm [17] which reduces computational time significantly.

In the ship routing optimization field, academic research concentrates on using these algorithms along with weather forecasts for wave and wind data (i.e. Padhy [18], Szłapczyńska and Śmierzchalsk [19], Takashima [20], Wei & Zhou [21], Mannarini [22], as well as Larsson and Simonsen [23]) cover examination for large distance routes.

On the contrary, Grifoll's research team [24] took a closer approach to Short Sea Shipping (SSS) optimization, with the creation of a MatLab script called SIMROUTE as a weather ship routing. Moreover, Basiana's dissertation [25] studied the feasibility of SIMROUTE which obtained different results depending on the wave height, wave direction, and ship's speed.

In 2018, Boren's work [26] compared the different emission assessment methodologies in the SSS framework and created the emission calculation tool *make_emissions.m* for SIMROUTE. Inspired by the STEAM methodology [27], it concluded that it was the least factor dependent methodology since it depends on the type of fuel, specific fuel oil consumption, and engine load, thus, using more specific data and obtaining more accurate calculations. Later on, in 2019 Borén [28] compared the different parametrizations of the wave effect on navigation for weather ship routing and implemented Aertssen, Khoklov, and Bowditch's formulations.

In parallel to this, in 2018 there was previous work by the author of this project on AIS data implementation for the International Association of Maritime Universities Student Conference (IAMUS Conference). [29] The presentation brought a first approach to the current work, carrying out different comparisons between real routes and optimum ones by manually introducing a database of routes. Also, the previous End of Degree Project in 2020 [30], went further and introduced three new MatLab modules to SIMROUTE in order to use AIS data and carry out route comparison studies.

1.3.2 SIMROUTE as an alive research software

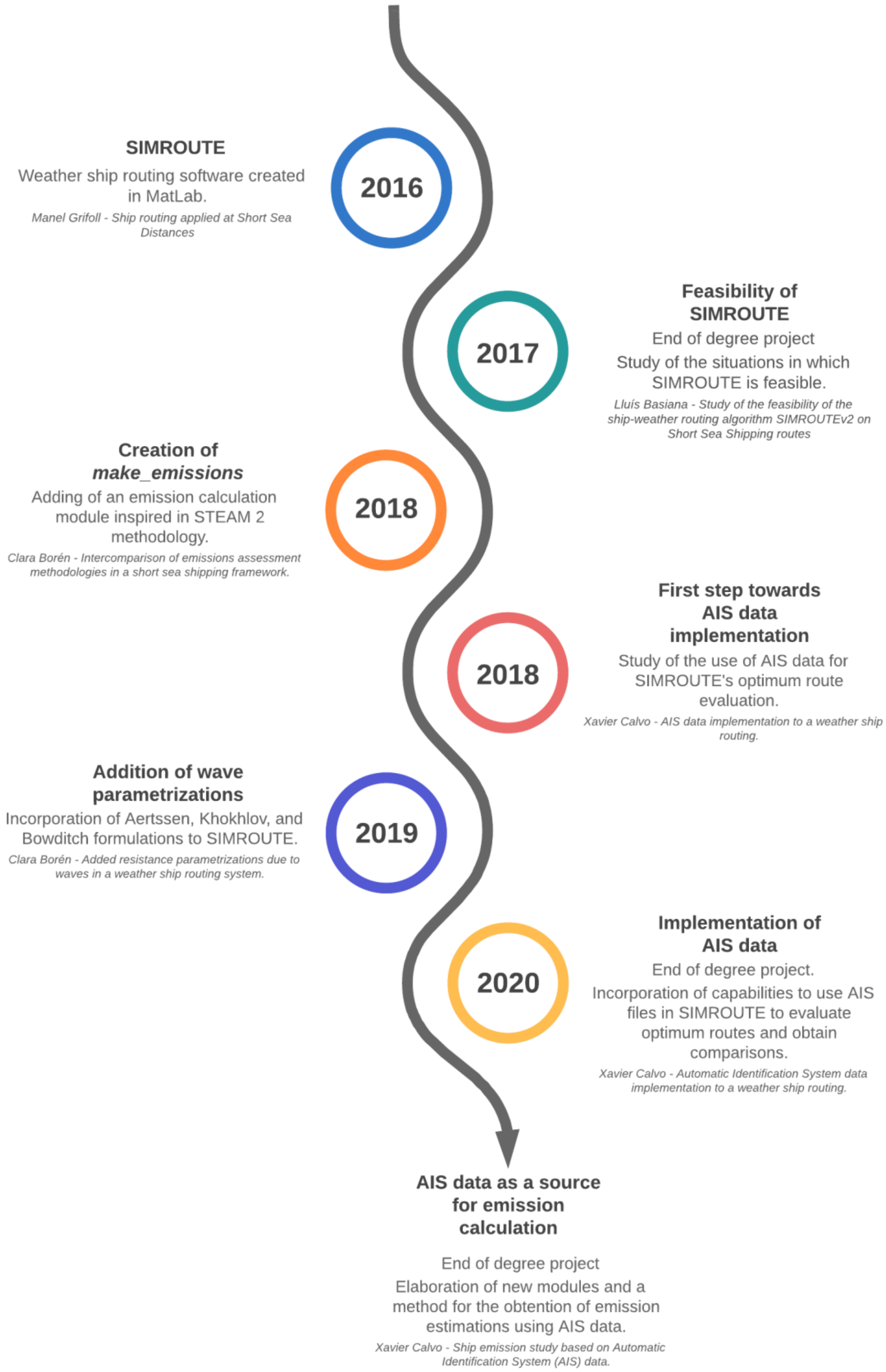


Figure 3 – Timeline of the evolution of SIMROUTE as a shared research software. As it is available for researchers and students it serves as an interesting tool for the study of weather ship routing, ship behaviour and emissions.

1.4 Relevant emission regulations

In this section there is a summary of the relevant regulations to the emission of ships.

1.4.1 Maritime Environment Protection Committee

The Maritime Environment Protection Committee (MEPC) is the IMO's senior technical body on marine pollution related matters and it is aided in its work by a number of IMO's Sub-Committees, in particular the Sub-Committee on Pollution Prevention and Response (PPR). [31]

Originated for the prevention of marine pollution by oil it resulted in the creation of the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973. During the years, it has adopted a variety of new measures that cover pollution from chemicals, other harmful substances, garbage, sewage and, under an Annex VI in 1997, it adopted measures for air pollution and emissions from ships.

The regulations under Annex VI for the Prevention of Air Pollution from Ships seek to minimize airborne emissions from ships (SO_x, NO_x, ODS, VOC shipboard incineration) and their effects locally and globally. It entered into force on 19 May 2005 and had, afterwards, a significant reduction on emission limits in October 2008 entering into force on 1 July 2010. [32]

1.4.1.1 MARPOL Annex VI [33]

MARPOL Annex VI includes a progressive reduction globally in emissions of SO_x, NO_x, and particulate matter and also the introduction of Emission Control Areas (ECAs) which are used to thoroughly control emissions of air pollutants in designated sea areas of interest.

A summary of the Annex is written below:

1. Chapter 1. General
    a. Regulation 1. Application
    b. Regulation 2. Definitions
    c. Regulation 3. Exceptions and Exemptions
    d. Regulation 4. Equivalents
2. Chapter 2. Survey, Certification and Means of Control
    a. Regulation 5. Surveys
    b. Regulation 6. Issue of endorsement of Certificates and Statements of Compliance related to fuel oil consumption reporting
    c. Regulation 7. Issue of a Certificate by another party
    d. Regulation 8. Form of Certificates and Statements of Compliance related to fuel oil consumption reporting
    e. Regulation 9. Duration and validity of Certificates and Statements of Compliance related to fuel oil consumption reporting
    f. Regulation 10. Port State Control on Operational Requirements
    g. Regulation 11. Detection of Violations and Enforcement
3. Chapter 3. Requirements for control of emissions from ships
    a. Regulation 12. Ozone Depleting Substances
    b. Regulation 13. Nitrogen Oxides (NOx)

    c. Regulation 14. Sulphur Oxides (SOx) and Particulate Matter
    d. Regulation 15. Volatile Organic Compounds (VOCs)
    e. Regulation 16. Shipboard Incineration
    f. Regulation 17. Reception Facilities
    g. Regulation 18. Fuel Oil Availability and Quality
4. Chapter 4. Regulations on Energy Efficiency for Ships
    a. Regulation 19. Application
    b. Regulation 20. Attained Energy Efficiency Design Index (Attained EEDI)
    c. Regulation 21. Required EEDI
    d. Regulation 22. Ship Energy Efficiency Management Plan (SEEMP)
    e. Regulation 22A. Collection and reporting of ship fuel oil consumption data
    f. Regulation 23. Promotion of technical co-operation and transfer of technology relating to the improvement of energy efficiency of ships
    g. Regulation 25. Verification of compliance

For the case of this project, the relevant regulations are those which cover the emissions produced by the exhaust gases from ships.

To highlight important information, next a few regulations are presented:

Regulation 2. Definitions

Here there are the definitions for:

- 7. **Emissions**: means any release of substances, subject to control by this Annex, from ships into the atmosphere or sea.
- 8. **Emission Control Area**: means an area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from NOx or Sox and particulate matter or all three types of emissions and their attendant adverse impacts on human health and the environment. Emission Control Areas shall include those listed in, or designated under, regulations 13 and 14 of this Annex.
- 9. **Fuel Oil**: means any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship, including gas, distillate and residual fuels.

Regulation 3. Exceptions and Exemptions

This regulation covers an exemption from Ship Emission Reduction for conducting trials for the development of ship emission reduction and control technology and engine design programmes. This exemption will only be provided if the applications of the NOx Technical Code could impede research into these matters. Only the Administration will provide the permit and will not exempt the ship from reporting the emissions under regulation 22A.

Regulation 13. Nitrogen Oxides (NOx) (as summarized by [34])

This regulation is relevant for diesel engines with a power output higher than 130 kW, which are installed on a ship or constructed on or after 1 January 2000 and diesel engines with a power output higher than 130 kW which undergo a major conversion on or after 1 January 2000. It does not apply to marine diesel engines for emergencies and marine diesel engines on ships that only engage on voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly.

This regulation considers a three-tiered approach which relies on the rated engine speeds (n) given in revolutions per minute. The emission limits are shown below:

Table 1 – Summary table of the NO_x limits in MARPOL's Annex VI. Source: [34]

Regulation	NOx limit	Rpm
Tier 1	17 g/kWh	n < 130
	$45\ n^{-0.2}$ g/kWh	130 ≤ n < 2000
	9.8 g/kWh	n ≥ 2000
Tier 2	14.4 g/kWh	n < 130
	$44\ n^{-0.23}$ g/kWh	130 ≤ n < 2000
	7.7 g/kWh	n ≥ 2000
Tier 3	3.4 g/kWh	n < 130
	$9\ n^{-0.2}$ g/kWh	130 ≤ n < 2000
	2 g/kWh	n ≥ 2000

For:

- Tier 1: the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the limits.
- Tier 2: the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the limits.
- Tier 3: in an emission control area designated for Tier 3 NO_X control under paragraph 6 of this regulation (NO_X Tier 3 emission control area), the operation of a marine diesel engine that is installed on a ship is prohibited except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the limits.

The emission control areas relevant for NO_x Tier 3 are the North American Emission Control Area, the United States Caribbean Sea Emission Control Area, the Baltic Sea Emission Control Area, and the North Sea Emission Control Area.

Regulation 14. Sulphur Oxides (SO_x) and Particulate Matter [33]

This regulation has been applicable from 1 March 2020 and it states the maximum sulphur content of fuel oil used by ships and for Emission Control Areas.

According to Reg. 14:

‘1 The sulphur content of fuel oil used or carried for use on board a ship shall not exceed 0.50% m/m.’

However, there are special requirements for the ECAs:

‘4 While a ship is operating within an emission control area, the sulphur content of fuel oil used on board that ship shall not exceed 0.10% m/m.’

Leaving the regulation on fuel oil sulphur with this timeline:

Table 2 – Summary table of the different regulations for fuel oil sulphur content. Source: [34]

Legislation	Region	Heavy fuel oil	
		S %	Impl. date
EU Directive 2005/33	SECA - Baltic Sea	1.5	11/8/2006
	SECA - North Sea	1.5	11/8/2007
	Outside SECA's	None	
Marpol Annex VI	SECA - Baltic Sea	1.5	19/5/2006
	SECA - North Sea	1.5	21/11/2007
	Outside SECA	4.5	19/5/2006
	SECA	1	1/3/2010
Marpol Annex VI Amendments	SECA	0.1	1/1/2015
	Outside SECA	3.5	1/1/2012
	Outside SECA	0.5	1/3/2020

Chapter 4. Regulations on Energy Efficiency for Ships [33]

This chapter sets out measures for the obtainment of Energy Efficiency Design Index (EEDI) for new ships or for those ships that have undergone a major conversion in Regulation 20.

An EEDI is a measure of the ship’s energy efficiency in (g/t·nm), the formula for its calculation can be obtained in Resolution MEPC.308(73).

In regulation 21 of chapter 4, there is information of the required EEDI depending on the type of ship and establishes four phases of EEDI limits starting from 1 Jan 2013 until 1 Jan 2025 onwards.

To continue, regulation 22 introduces the obligation of a Ship Energy Efficiency Management Plan (SEEMP) from 31 December 2018 and in the case of a ship of 5,000 gross tonnage and above, and shall include the methodology for the collection of data required under regulation 22A. In 2016, there was the first introduction of the Guidelines for the development of a Ship Energy Efficiency Management Plan.

As stated by [35] 'there are two parts to a SEEMP. Part I provides a possible approach for monitoring ship and fleet efficiency performance over time and some option to be considered when seeking to optimize the performance of a ship. Part II provides the methodologies ships of 5,000 gross tonnage and above should use to collect the data required pursuant to regulation 22A of Marpol Annex VI and the processes that the ship should use to report the data to the ship's Administration or any organization duly authorized by it.'

Regulation 22A. Collection and reporting of ship fuel oil consumption data [33]

This regulation states that: 'From calendar year 2019, each ship of 5,000 gross tonnage and above shall collect the data specified in appendix IX to this Annex, for that and each subsequent calendar year or portion thereof, as appropriate, according to the methodology included in the SEEMP.'

Appendix IX Information to be submitted to the IMO Ship Fuel Oil Consumption Database:

Identity of the ship

IMO number

Period of calendar year for which the data is submitted

Start date (dd/mm/yyyy)

End date (dd/mm/yyyy)

Technical characteristics of the ship

Ship type, as defined in regulation 2 of this Annex or other (to be stated)

Gross tonnage (GT)

Net tonnage (NT)

Deadweight tonnage (DWT)

Power output (rated power) of main and auxiliary reciprocating internal combustion engines over 130 kW (to be stated in kW)

EEDI (if applicable)

Ice class

Fuel oil consumption, by fuel oil type 6 in metric tonnes and methods used for collecting fuel oil consumption data.

Distance travelled

Hours underway

1.3.2 European Environment Agency

According to them [36] [37] 'the European Environment Agency (EEA) aims to support sustainable development by helping to achieve significant and measurable improvement in Europe's environment, through the provision of timely, targeted, relevant, and reliable information to policymaking agents and the public.'

In other words, the EEA is an organization that supports the European Union in the transition to a more sustainable economy, it does this by cooperating and providing an information and observation network, and helping make informed decisions that will translate into new regulations.

1.3.2.1 Regulation (EU) 2015/757 on the monitoring, reporting and verification (MRV) of carbon dioxide emissions from maritime transport. [38]

This regulation lays down rules for the accurate monitoring, reporting and verification of carbon dioxide (CO_2) emissions and of other relevant information from ships arriving at, within and departing from ports under the jurisdiction of a Member State, in order to promote the reduction of CO_2 emissions from maritime transport in a cost effective manner.

Those ships of 5,000 GT and above must report their CO_2 emissions for those voyages to/from EU port of calls. This monitorization entered in force on 1 January 2018, and has to be communicated in the form of the following parameters:

- Fuel consumption (port/sea)
- Transport work (based on actual cargo carried)
- Distance
- Time

Finally, these reports are sent to the European Commission with a previous verification by independent accredited organizations, and posteriorly are certified with a Document of Compliance and published on a public database. The following is a summary of the regulation for MRV.

1. Chapter I. General provisions
    a. Article 1. Subject matter
    b. Article 2. Scope
    c. Article 3. Definitions
2. Chapter II. Monitoring and reporting
    a. Section 1. Principles and methods for monitoring and reporting
        i. Article 4. Common principles for monitoring and reporting
        ii. Article 5. Methods for monitoring CO_2 emissions and other relevant information
    b. Section 2. Monitoring plan
        i. Article 6. Content and submission of the monitoring plan
        ii. Article 7. Modifications of the monitoring plan
    c. Section 3. Monitoring of CO_2 emissions and other relevant information
        i. Article 8. Monitoring of activities within a reporting period
        ii. Article 9. Monitoring on a per-voyage basis
        iii. Article 10. Monitoring on an annual basis
    d. Section 4. Reporting

        i. Article 11. Content of the emissions report
        ii. Format of the emissions report
3. Chapter III. Verification and accreditation
    a. Article 13. Scope of verification activities and verification report
    b. Article 14. General obligations and principles for the verifiers
    c. Article 15. Verification procedures
    d. Article 16. Accreditation of verifiers
4. Chapter IV. Compliance and publication of information
    a. Article 17. Document of compliance
    b. Article 18. Obligation to carry a valid document of compliance on board
    c. Article 19. Compliance with monitoring and reporting requirements and inspections
    d. Article 20. Penalties information exchange and expulsion order
    e. Article 21. Publication of information and Commission report
5. Chapter V. International cooperation
    a. Article 22. International cooperation
6. Chapter VI. Delegated and implementing powers and final provisions
    a. Article 23. Exercise of delegation
    b. Article 24. Committee procedure
    c. Article 25. Amendments to Directive 2009/16/EC
    d. Article 26. Entry into force
7. Annex I. Methods for monitoring CO_2 emissions
8. Annex II. Monitoring of other relevant information
9. Annex III. Elements to be taken into account for the delegated acts provided for in Article 15 and 16

Chapter 2. Methods

This chapter will cover the methodologies considered for the development of the new modules produced in this project. Firstly, it will start with the AIS data approaches, with a small introduction of STEAM 2 methodology which has been introduced into SIMROUTE software. Secondly, the following section covers the extension of actual SIMROUTE's procedures for the calculation of emissions. Thirdly, the EMEP/EEA guidebook is summarized with methods for the estimation of emissions from fuel consumption, and from navigation data and engine installed power. Finally, these AIS and annual emission calculation techniques are merged and transformed into the proposed methodology for this work. In addition, there is an explanation for the functions of the new modules and a guide on how to use them.

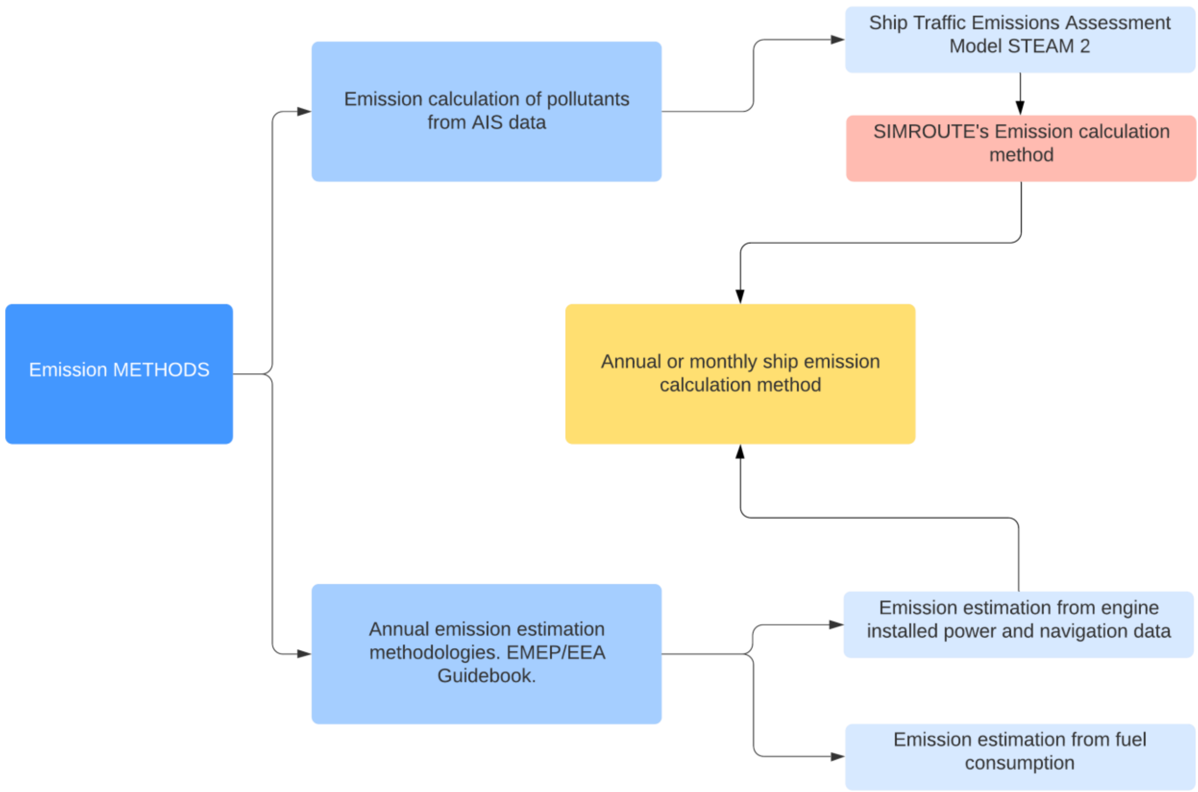


Figure 4 – Outline for the elaboration of the project's methodology.

2.1 Emission calculation of pollutants by ships with AIS data

2.1.1 Ship Traffic Emissions Assessment Model 2 (STEAM 2)

The STEAM 2 is a model for the calculation of emissions using the messages provided by the Automatic Identification System and is applicable to evaluate the ship emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon dioxide (CO_2), particulate matter (PM), and carbon monoxide (CO).

In [39] the author proposes a methodology for the evaluation of ship specifications, engine power and auxiliary power depending on the availability of data. The model assumes all main engines to be identical, and the load values are assumed to be less or equal than 85%. Then, it calculates the fuel consumption by the product of the constant specific fuel oil consumption (SFOC) and the instantaneous engine power. The minimum for the SFOC is found at the relative engine loads 70, 75 and 80% depending on the manufacturer.

2.1.2 SIMROUTE Emission calculation method

The SIMROUTE's module, *make_emissions.m* that is currently available [13] has been inspired by STEAM 2 methodology [39]. The script can obtain the amount of Sulphur dioxide (SO_2), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter generated per trip in optimum and minimum distance routes. The aim of this work is to update this module and include AIS obtained routes. In this section there will be an explanation of the method used by the *make_emissions.m* for power estimation and emission obtainment.

The input data is described below:

- Installed power per engine in kW
- Engine Load (assumed to be 80% when sailing at cruising speed)
- Design speed in knots
- Specific Fuel Oil Consumption (SFOC) in g/kWh
- Sulphur Content (SC) of fuel in mass percentage
- Carbon Content (CC) of fuel in mass percentage
- Engine Revolutions per Minute (RPM)
- Molar mass of Sulphur, Sulphur dioxide, Carbon and Carbon dioxide in g/mol

Emissions of CO_2 and SO_2 are calculated from the fuel consumption and Sulphur content, respectively.

If engine data is unavailable, the ship is assumed to use a 500rpm medium speed diesel engine by default. All the variables can be changed accordingly to any case study.

2.1.2.1 Engine power estimation method

The instantaneous power can be evaluated as a function of the vessel's speed [13].

$P_{Transient} = (CF + CR + CA + CAA)\left(\frac{1}{2}v^3 S\right)\frac{1}{\varepsilon_0}$ (N) (in SI units) *Equation 1*

Where:

CF: frictional resistance

CR: residual resistance

CA: appendage resistance

CAA: air resistance

ε_0: propulsive coefficient

S: wet surface of the ship

All these parameters are specific to the hull of each case, and are usually not found in available databases. [39] proposes an estimated solution for this, assuming that they are ship-specific constants. This new formula is expressed as follows:

$P_{transient} = kv^3$ (N) *Equation 2*

Where k is:

$k = \frac{\varepsilon_p \cdot P_{installed}}{(V_{design})^3}$ (N) *Equation 3*

Where:

$P_{installed}$: total installed power of main engines (kW)

ε_p: engine load at Maximum Continuous Rating (MCR) of main engines

V_{design}: design speed (m/s)

v : instantaneous speed (m/s)

The software calculates the average transient power in terms of the vessel's speed by getting the information from the introduced route files. Next, the fuel consumption (FC) is calculated for the routes, using this formula:

$FC = P_{transient} \cdot SFOC \cdot Time$ *Equation 4*

Where:

FC : Fuel consumption (in g converted into T for displaying)

$P_{transient}$: Instantaneous power (in kW)

SFOC: Specific Fuel Oil Consumption (in g/kWh)

Time: Trip duration (in hours)

2.1.2.2 Emission Factors calculation

The following emission factors can be found in SIMROUTE's Technical Guide (13) but have been inspired from STEAM methodology [27]

- **SO_2**
  SFOC: Specific Fuel Oil Consumption (g/kWh)
  SC: Sulphur content of fuel (mass %)
  M(S): Molar mass of sulphur (g/mol)
  m(S): mass of sulphur (g)
  $M(SO_2)$: Molar mass of sulphur dioxide (g/mol)
  n(S): number of mols of sulphur (mol)
  $n(SO_2)$: number of mols of sulphur dioxide (mol)
  $m(SO_2)$: mass of sulphur dioxide (g)

  Note that:

  $n(S) = \frac{m(S)}{M(S)}$ (mol) *Equation 5*

  The sulphur combustion stoichiometric formula, for a mol of sulphur burnt, there will be a mol of sulphur dioxide generated:

  $S + O_2 \rightarrow SO_2$, that is $n(S) = n(SO_2)$ *Equation 6*

  To continue, the mass of sulphur burnt per kW in an hourly basis is obtained by multiplying the Specific Fuel Oil Consumption of the engine with the Sulphur Content of the fuel burnt:

  $m(S) = SFOC \cdot SC$ (g/kWh) *Equation 7*

  The emission factor for SO_2 is, then, obtained by multiplying the molar mass by the number of mols of SO_2.

  $EF(SO_2) = M(SO_2) \cdot n(SO_2) = M(SO_2) \cdot n(S) = M(SO_2) \cdot \frac{SFOC \cdot SC}{M(S)}$ (g/kWh) *Equation 8*

- **CO_2**
  The process for the obtainment of the emission factor is similar to the sulphur dioxide one.
  SFOC: Specific Fuel Oil Consumption (g/kWh)
  CC: Carbon content of fuel (mass %)
  M(C): Molar mass of carbon (g/mol)
  m(C): mass of carbon (g)
  $M(CO_2)$: Molar mass of carbon dioxide (g/mol)
  n(C): number of mols of carbon (mol)
  $n(CO_2)$: number of mols of carbon dioxide (mol)
  $m(CO_2)$: mass of carbon dioxide (g)

  $$n(C) = \frac{m(C)}{M(C)} = \frac{SFOC \cdot SC}{M(C)}$$
  $$n(C) = n(CO_2)$$

$EF(CO_2) = M(CO_2) \cdot n(CO_2)$ *Equation 9*

- **NO_x**

  The NOx depends on the speed rotation of the engine (REFERENCE IMO, 1997).

$$\text{NOx Emission Factor (g/kWh)} = \begin{cases} 17, \text{ for engines less than 130rpm} \\ 45.0\text{^}n^{-0.2}, \text{ for engines } 130<n<2000,\ n= \text{ engine rpm} \\ 9.8 \text{ for engines over 2000 rpm} \end{cases}$$

Equation 10

- **PM**

  Particulate matter is divided into Elementary Carbon (EC), Organic Carbon (OC), Ash, Sulphate (SO_4) and associated water (H_2O).

  According to [27], a linear regression to the data presented by Buhaug et al. (2009) can be applied, giving the following emission factor dependencies:

$$EF_{SO_4} = 0.312S$$
$$EF_{H_2O} = 0.244S$$

Where S is the fuel sulphur content in percentages:

$$OC_{EF} = \begin{cases} 3.333, EL < 0.15 \\ \frac{a}{1+be^{-cEL}}, EL \geq 0.15 \end{cases}$$

Equation 11

Where a, b and c are dimensionless constants (a=1024, b=47600, c=32547).

$$EF_{EC} = 0.08\ g/kWh$$
$$EF_{OC} = 0.2\ g/kWh$$
$$EF_{ash} = 0.06\ g/kWh$$

The emission coefficients for EC, OC and ash have been assumed to be independent of the Sulphur content. However, for the emission coefficient for OC, an additional dependency on engine load is used.

The total PM emission factor is assumed to be the sum of all the above emission factors:

$EF_{PM} = SFOC_{REL}(EF_{SO4} + EF_{H2O} + EF_{OC}OC_{EL} + EF_{EC} + EF_{ASH})$ *Equation 12*

Where:

$$SFOC_{REL} = 0.455EL^2 - 0.71EL + 1.28$$

$SFOC = SFOC_{REL} \cdot SFOC_{MANUFACTURER}$ *Equation 13*

It is assumed that the NOx emission factors of all engines, regardless of their year of construction can be computed based on the IMO curve and are independent of the fuel consumption. However, the predictions of the emissions of SO_2, CO_2 and PM are based on engine-specific fuel consumption [26].

- **Summary of emission factors**

Table 3 – Summary table of the emission factors presented above.

Sulphur dioxide (SO_2)	$\boldsymbol{EF(SO_2) = M(SO_2) \cdot n(SO_2) = M(SO_2) \cdot n(S) = M(SO_2) \cdot \frac{SFOC \cdot SC}{M(S)}}$ (g/kWh)
Carbon dioxide (CO_2)	$EF(CO_2) = M(CO_2) \cdot n(CO_2)$
Nitrogen oxides (NO_x)	$17, for\ engines\ less\ than\ 130\ rpm$ $45^{n^{-0.2}}\ for\ engines\ 130 < n < 2000, n = engine\ rpm$ $9.8\ for\ engines\ over\ 2000\ rpm$
Particulate Matter (PM)	$EF_{PM} = SFOC_{REL}(EF_{SO4} + EF_{H2O} + EF_{OC}OC_{EL} + EF_{EC} + EF_{ASH})$ Where: $SFOC_{REL} = 0.455EL^2 - 0.71EL + 1.28$ $SFOC = SFOC_{REL} \cdot SFOC_{MANUFACTURER}$

2.2 Emission calculation method for a year. European Environment Agency (EEA) [9]

The EMEP/EEA air pollutant emission inventory guidebook and, more precisely, the Chapter 1.A.3.d Navigation, can be considered as a reference for emission estimate at international level.

This guidebook presents a three-tiered methodology depending on the availability of data. Tier 3 is classified as 'ship movement' methodology, this type must be used when there is detailed ship movement data available, as well as technical information about the ships (that is, for example, engine size and technology, power installed or fuel use, or hours in different activities).

For commercial vessels, the EMEP/EEA guidebook proposes that the yearly emissions of a ship can be calculated on a trip by trip basis. Therefore, expressing the emissions for one trip as follows:

$$\boldsymbol{E_{trip}} = \boldsymbol{E_{hotelling}} + \boldsymbol{E_{manoeuvring}} + \boldsymbol{E_{cruising}} \quad \textit{Equation 14}$$

However, due to the fact that calculating the yearly emissions for a high number of ships (which would be the case for a national emission study) would be time and resource consuming, a representative period of the year and a representative sample of vessels can be used to scale up the total emissions for all trips and vessels over a year.

In order to estimate the emissions, it can be done either from the fuel consumption data (if available) or from the engine power. The following are the two methodologies presented in a step-by-step mode:

2.2.1 Emission estimation from fuel consumption

The following steps are required to estimate emissions from fuel consumptions. This procedure is applicable only where detailed information about fuel consumptions for each ship/engine type combination in the different navigation phases is available; otherwise the engine power-based procedure presented below should be used.

1. Obtain fuel consumption for each individual ship, engine type/fuel class and ship activity. This may be done for the whole year or a representative sample of the year, for all ships or for a representative sample of the ships for each ship category and engine type/fuel class. This choice may depend on the resources available and the required accuracy of the study.
2. Calculate emissions for each ship category and engine type/fuel class multiplying by the emission factors.

This methodology is only useful when there is accurate information about the fuel consumptions available and it is put together with emission factors supplied by the Guidebook.

2.2.2 Emission estimation from engine installed power and navigation data

On the other hand, when the fuel consumption per trip is unavailable, the following steps are proposed in order to calculate the emissions based on installed power and the navigation:

1. Obtain ship movement data: place of departure, place of arrival, time of departure and time of arrival for each individual ship. This may be done for the whole year or a representative sample of the year, for all ships or for a representative sample of the ships. This choice will depend on the resources available and the required accuracy of the study.
2. Determine the sailing routes and distances between ports.

3. Characterize each ship by category and engine type/fuel class, and record the installed main or auxiliary engine power. A ship register, giving the size and engine type of individual ships, is useful for this. Such a register of the national fleet should be available in most countries but usually only covering national ships. Lloyds Register’s Register of Ships will provide details of national and international shipping greater than 100 GT. If engine power is unknown, and only gross tonnage (GT) is available, installed main engine power can be obtained from tables provided in the guidebook.
4. Determine the total sailing time for each ship category and engine type/fuel class, either based on the distance and average cruise speed or time of departure and arrival. The choice should be based on an assessment of the quality of the data.
5. Determine total hotelling and manoeuvring time for each ship category and engine type/fuel class by port survey or on the basis of average time spent values provided in the guidebook.
6. Calculate emissions for each ship category and engine type/fuel class multiplying total time spent in each phase as determined in previous steps 4 and 5 by the installed main and auxiliary engine power, for each ship category, calculated as determined in step 3, load factors (and for main engine % time of operation) and emission factors.

Also, in this case, the EMEP methodology is laying out a way of calculating emissions in a big scale in a whole-country basis, it does this by using emission factors and ratios to estimate ship characteristics from the available information sources. However, the steps shown above serve as an idea to propose a new methodology to be applied for the tools available in SIMROUTE. The access to AIS information of the routes of ships, and to a methodology which proposes emission factors for this type of ship waypoint data, is an opportunity to merge these ideas in order to calculate the annual emissions in a more specific way, either for a ship, a fleet, or an area.

2.3 Annual or monthly ship emission calculation method

After the introduction of the aforementioned methodologies: the AIS emission calculation method, the SIMROUTE's approach with optimum and minimum distance emission calculation, and the EMEP/EEA guidebook for the calculation of the emissions from navigation in a yearly basis. This work proposes a fusion of these methods by using AIS data to obtain the emissions produced ship navigation for a whole year. Note that SIMROUTE's methodology does not include the calculation of the emissions produced during hotelling and manoeuvring.

Below is the methodology for the obtainment of yearly emissions for a ship from AIS data:

1. Select ship or ships for the study.

2. Obtain ship information: engine power, lowest possible Specific Fuel Oil Consumption (SFOC) and the engine load (EL) for that SFOC, and, finally, the Sulphur and Carbon content of the Fuel Oil used by the ship. According to [39] 'the minimum of EL is located approximately at the relative engine load of 70, 75 and 80%.' The recommended SFOC and EL can usually be obtained from the corresponding manufacturer's project guide of the engine.

3. Depending on the assessment of the quality of the calculation, set a year or a representative period of the year. For example, use a representative month of each season of the year.

4. Obtain the selected ship's routes for that selected period/s of time. These can be obtained from various AIS online databases such as Marine Traffic (www.marinetraffic.com) or Vessel Finder (www.vesselfinder.com), or shore-station AIS databases.

5. Use SIMROUTE's (make_emissions.m) [13] proposed methodology for all routes, which has been inspired by STEAM 2 [39] but does not include hotelling and manoeuvring.
    a. Obtain Instantaneous Power (Equations 2 and 3)

    b. Obtain Fuel Consumption (Equation 4):

    c. Obtain Emission Factors (EF):

Table 4 – Summary table for the emission factors used in the proposed methodology.

SO_2	$EF(SO_2) = M(SO_2) \cdot n(SO_2) = M(SO_2) \cdot n(S) = M(SO_2) \cdot \frac{SFOC \cdot SC}{M(S)}$ (g/kWh)
CO_2	$EF(CO_2) = M(CO_2) \cdot n(CO_2)$
NO_x	$17, for\ engines\ less\ than\ 130\ rpm$ $45^{n^{-0.2}}\ for\ engines\ 130 < n < 2000, n = engine\ rpm$ $9.8\ for\ engines\ over\ 2000\ rpm$
PM	$EF_{PM} = SFOC_{REL}(EF_{SO4} + EF_{H2O} + EF_{OC}OC_{EL} + EF_{EC} + EF_{ASH})$ Where: $EF_{SO4} = 0.312 \cdot SulphurContent(SC)$

$$EF_{H2O} = 0.244 \cdot SulphurContent(SC)$$
$$SFOC_{REL} = 0.455EL^2 - 0.71EL + 1.28$$
$$SFOC = SFOC_{REL} \cdot SFOC_{MANUFACTURER}$$

d. Obtain emissions in tons:

Table 5 – Summary table of the formulas for emission obtainment in tonnes.

SO_2	$SO_2 = \frac{Time \cdot P_{transient} \cdot EF(SO_2)}{10^{-6}}$ (Tons)
CO_2	$CO_2 = \frac{Time \cdot P_{transient} \cdot EF(CO_2)}{10^{-6}}$ (Tons)
NO_x	$NO_x = \frac{Time \cdot P_{transient} \cdot EF(NO_x)}{10^{-6}}$ (Tons)
PM	$PM = \frac{Time \cdot P_{transient} \cdot EF(PM)}{10^{-6}}$ (Tons)

6. Calculate the average emissions per month and calculate the approximate year emissions.

2.4 Optimized tools for emission calculation implementation into SIMROUTE

In this section, to fulfil the objectives of this project, there are three MatLab modules that carry out the methodology presented before. First of all, a script that groups all the obtained routes in months so that the second module can calculate the emissions for each route, month, and approximate emissions for the year. Finally, the third module obtains figures of hourly emissions with a colour bar so that the emission density can be evaluated.

2.4.1 monthly_route.m

This new tool to SIMROUTE, which has been created in this project, adds the ability to group routes into a file so that it can later be used for emission calculation in the next module. More specifically, this program will group the characteristics of downloaded *.csv* files containing information about ship routes into a *.mat* file. This type of (*.csv*) file can be obtained from an AIS source such as an online-based database or a shore-station database. The file shall have the input data presented in the following way:

a) Header: Timestamp,Source,Speed,Latitude,Longitude. (The order is not important as the script calls each variable by its name).
b) Data: date(yyyy-MM-dd HH:mm:SS), speed(xx.xx), course(xxx), latitude(xx.xxxx), longitude(xx.xxxx).

Table 6 - Example of a *.csv* file obtained from MarineTraffic. The data has been accessed via Microsoft Office's Excel program and presented here as a table. Each line of information only uses one cell.

Timestamp,Source,Speed,Course,Latitude,Longitude
2020-01-29 04:16:50,Terr-AIS,14.5,109,39.41891,-0.2781917
2020-01-29 04:21:26,Terr-AIS,16.6,76,39.42105,-0.2527583
2020-01-29 04:32:02,Terr-AIS,17.4,51,39.43914,-0.19026
2020-01-29 04:41:02,Terr-AIS,18.0,40,39.47389,-0.1534917
2020-01-29 04:50:38,Terr-AIS,17.2,43,39.50653,-0.1087083
2020-01-29 05:02:26,Terr-AIS,17.3,32,39.55163,-0.06571667
2020-01-29 05:11:40,Terr-AIS,17.3,35,39.58803,-0.03202333
2020-01-29 05:22:16,Terr-AIS,17.2,35,39.62947,0.006385
2020-01-29 05:31:16,Terr-AIS,17.3,38,39.66437,0.03966
2020-01-29 05:40:04,Terr-AIS,17.3,39,39.6972,0.07463167
2020-01-29 05:49:38,Terr-AIS,16.6,40,39.7285,0.1176633
2020-01-29 06:00:50,Terr-AIS,17.2,35,39.7729,0.15629
2020-01-29 06:10:26,Terr-AIS,17.1,35,39.80994,0.191535
2020-01-29 06:20:01,Terr-AIS,17.0,35,39.84719,0.2259383
2020-01-29 06:29:26,Terr-AIS,17.1,35,39.88382,0.2595767
2020-01-29 06:39:50,Terr-AIS,17.2,35,39.92416,0.2969767

Once the script is run, the output will let the user know that it has finished with the elapsed time:

'Elapsed time is 1.931894 seconds.'

See Annex 1 for the complete code.

2.4.2 make_emissions_yearly

Additionally, a new contribution to SIMROUTE and created in this project is the *make_emissions_yearly.m* module which will plot in the command window of MatLab the obtained emissions in a route-by-route basis, as well as a month-by-month and an approximate of the year emissions based on the average monthly emissions value. This module supposes a great time-saving tool since it will perform a large amount of calculations in a short period of time, which can be especially important for large-scale emission studies.

The inputs for this module will be:

- A *.mat* file containing the routes made by the ship or group of ships in one month which can be obtained using the module explained before (*monthly_route.m*). This can be just one file or up to 12 files (12 months of the year).
- Data about the engine and Fuel Oil content:
  - Engine load in unit percentage, to be introduced in *EL*.
  - Engine power in kW, to be introduced in *Pow_Ins*.
  - Design speed of the ship, to be introduced in *V_design*.
  - Specific Fuel Oil Consumption in g/kWh, to be introduced in *SFOC*.
  - Engine revolutions per minute in rpm, to be introduced in *Engine_RPM*.
  - Sulphur content of the Fuel Oil (FO) in % mass, to be introduced in *SC*.
  - Carbon content of the FO in % mass, to be introduced in *CC*.

The output of the script will be the emissions for every route, month and approximate for the year. This is a small example:

```
  'month1'
  'route1'
Fuel consumption has been: 4.133 Tn
CO2 have been: 13.0481 Tn
SO2 have been: 0.38975 Tn
NOx have been: 0.4038 Tn
PM have been: 0.0089405 Tn
  'route2'
Fuel consumption has been: 115.0547 Tn
CO2 have been: 363.2335 Tn
SO2 have been: 10.8499 Tn
NOx have been: 11.241 Tn
PM have been: 0.24889 Tn
Month 1 fuel consumption has been: 288.2902 Tn
    CO2 emissions have been: 910.1473 Tn
    SO2 emissions have been: 27.1863 Tn
    NOx emissions have been: 28.1663 Tn
    PM emissions have been: 0.62363 Tn
Year fuel consumption has been: 3459.4827 Tn
   CO2 emissions have been: 10921.7672 Tn
   SO2 emissions have been: 326.2358 Tn
   NOx emissions have been: 337.9954 Tn
   PM emissions have been: 7.4835 Tn
```

See Annex 2 for the complete code.

2.4.3 make_emissions_map

Finally, a third module, which has also been created in this project, is the *make_emissions_map.m*. This module will plot the emissions produced during the months introduced in an hourly emission rate basis. This plotting has a colour bar which will help identify those high emission periods for the ship. The module actually produces the outline of the Mediterranean, or the desired coordinates in Europe and plots coloured circles depending on the hourly emission rate, its use will create five figures for the correspondent emissions of CO_2, SO_2, NO_x, and Particulate Matter but also the hourly fuel consumption. The inputs will be the same as in the *make_emissions_yearly* plus the desired coordinates of the area that the figure should plot.

The inputs for this module will then be:

a) A *.mat* file containing the routes made by the ship or group of ships in one month which can be obtained using the module explained before (*monthly_route.m*). This can be just one file or up to 12 files (12 months of the year).
b) Data about the engine and Fuel Oil content:
    - Engine load in unit percentage, to be introduced in *EL*.
    - Engine power in kW, to be introduced in *Pow_Ins*.
    - Design speed of the ship, to be introduced in *V_design*.
    - Specific Fuel Oil Consumption in g/kWh, to be introduced in *SFOC*.
    - Engine revolutions per minute in rpm, to be introduced in *Engine_RPM*.
    - Sulphur content of the Fuel Oil (FO) in % mass, to be introduced in *SC*.
    - Carbon content of the FO in % mass, to be introduced in *CC*.
c) The desired area of plotting by defining the maximum and minimum latitude and longitude in: LonMin, LonMax, LatMin, and LatMax.

Once the program is run, an example of the output figures is shown in Figure 4.

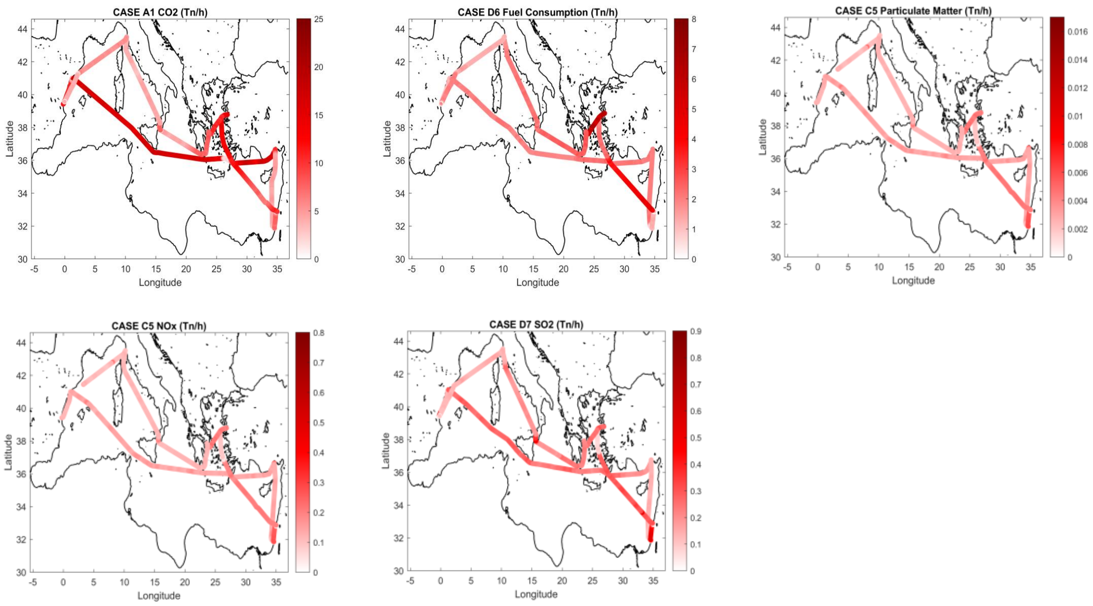


Figure 5 – Examples of the figures obtained from *make_emissions_map.m*. The module will produce figures for the hourly rate consumption and emission of pollutants.

See Annex 3 for the complete code.

2.5 New SIMROUTE User's guide proposition for Annual emission calculation

The SIMROUTE software, which is MatLab-based, incorporates two short guides in its 'Documentation' folder which allow new researches make use of the tools included in the program.

Firstly, the SIMROUTE TECHNICAL MANUAL [13] instructs one on the theory that is behind the code: the basis and algorithm of an optimum pathfinder, wave interaction and parametrization for its incidence to the ship, useful tips for the use of the scripts, and theory on the emissions of pollutants obtained from the script *make_emissions.m.*

Secondly, the SIMROUTE USER'S MANUAL [14] is a short course on SIMROUTE, with an explanation on what it is, how it is placed in the educational framework, its different scripts and their functions, and a step-by-step guide with some examples.

Having introduced what these guides contain, the project presented in this paper proposes here an update to this SIMROUTE User's Manual which will incorporate a step-by-step guide on the use of these newly added tools (also introduced by this work) to obtain an annual approximation of the emissions produced by a ship or multiple. In addition, there will also be a short flow chart for the obtainment of annual emissions.

2.5.1 Step-by-step guide of SIMROUTE Use for Annual ship emission calculation

The following is the new proposed step-by-step guide (which has been introduced by this work) for the calculation of annual ship emissions using AIS routes:

1. Obtain a *.csv* file containing the desired route to obtain emissions from. Remember it must have the following data: date and time, speed, course, latitude, and longitude. The file can be obtained from any AIS source such as the FNB's AIS station, the Marine Traffic website (www.marinetraffic.com) available through the FNB's login details, Vessel Finder (www.vesselfinder.com), IHS Fairplay, and Lloyd's Maritime Information Service (LMIS). Note that not all sources are free of use.
2. Open MATLAB. Open *start.m* inside SIMROUTE's folder and run it.
3. In case you would like to recover data from the routes used, open *AIS_route_analysis.m* and obtain time and dates of departure and arrival, coordinates of origin and destination, total time of the route, total distance, and average speed. To do so, write the name of the *.csv* file onto the variable called *filename*. Run it.
4. Open *Monthly_route.m*. Introduce the names of the desired *.csv* files in the variable *ARX* and give a name to the output file in *arxiu_out*. Run it. This module will the group the introduced routes into one package file in *.mat* format. In order to obtain annual emission estimation, it would be desirable to group the routes into months and obtain the total routes of the studied ship for each month. It can be done for the whole year or for a representative part of it.
5. Obtain ship engine and fuel data. This can be obtained from the direct source (i.e. the shipowner or the engine manufacturer), or other paid databases such as the IHS Fairplay or the Lloyd's Maritime Information Service (LMIS). The needed data will be:
    a. Engine load (in unit percentage): According to the data of Caterpillar the minimum specific fuel oil consumption is situated at a determined engine load of 70 to 80%.
    b. Installed power (in kW).

   c. Design speed (knots).
   d. Specific Fuel Oil Consumption (g/kWh).
   e. Sulphur content of Fuel Oil. (in mass %).
   f. Carbon content of Fuel Oil (in mass %).
   g. Crankshaft revolutions per minute (rpm).
6. Open *make_emissions_yearly.m*. Introduce acquired data to the corresponding variables *EL* (Engine load), *Pow_Ins* (Installed power), *V_design* (Design speed), *SFOC* (Specific Fuel Oil Consumption), *SC* (Sulphur content), *CC* (Carbon content), and *Engine_RPM* (Crankshaft revolutions per minute). Then introduce the route package file names into the variable *ARX* following the format. Run it. You will now obtain the calculation for the FO consumption and emissions (in tons) in the following way:
   a. Route-by-route basis of each package.
   b. Month-by-month basis per package introduced.
   c. Annual estimated emissions and fuel consumption.
7. Open *make_emissions_map.m*. Introduce the same data as the used before in *make_emissions_yearly.m*, give a name to the output figures by assigning a name in the variable *nom*, and define the area you would like to visualize assigning the maximum coordinates for *LonMin* (minimum longitude), *LonMax* (maximum longitude), *LatMin* (minimum latitude), *LatMax* (minimum latitude). (The default coordinates are the area for the Mediterranean Sea). Run it. You will then obtain five figures corresponding to the FO consumption, and emissions of CO_2, SO_2, NO_x, and particulate matter. They will be saved in the folder with the address: *SIMROUTEv2/out/emissions/*.

2.5.2 Flow chart for Annual ship emission calculation

In the next page there is a flow chart outlining the guide proposed before, and which will be presented as an easier way to understand the process of calculation.

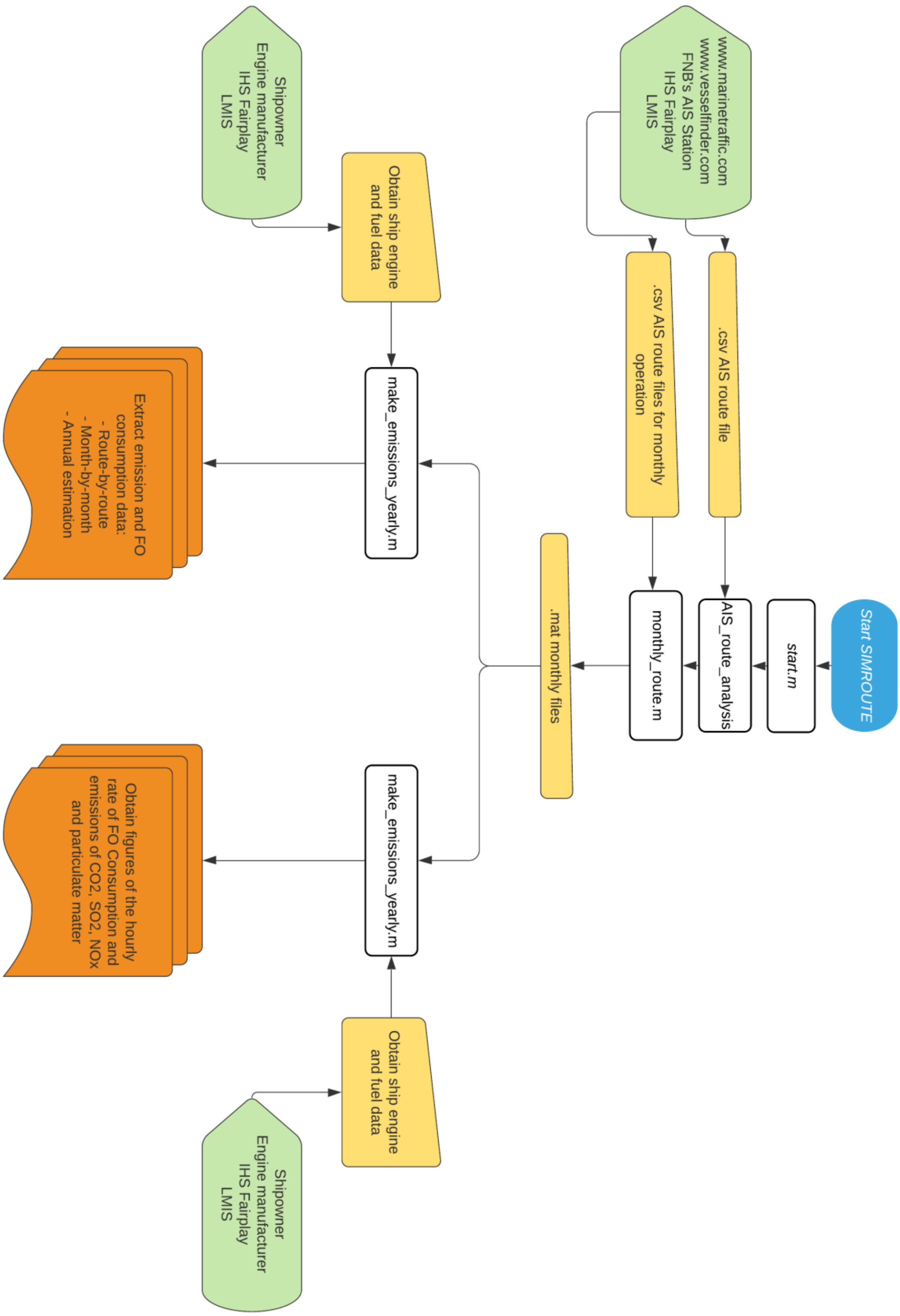


Figure 6 – Flow chart for annual ship emission calculation methodology.

2.6 Case study

In order to evaluate the new additions introduced in this work, a case study is carried out which uses the described methodology. For this purpose, 5 ships have been studied to obtain their year emissions. These ships all have the same characteristics and routes which cover the whole Mediterranean. The reason why these cases have been chosen is because their data has been provided by a fellow student that is doing research on their routes. However, they have asked to keep the name of the ships confidential. The following tables show the main data of the ship.

Table 7 - Characteristics of the ships chosen for the case study. The names of the ships have had to stay confidential.

Ship type	Container vessel	
Design Speed	19.6	kn
Length	260	m
DWT	50530	ton
Engine Manufacturer	MAN-B&W	
Engine model	8K90MC-C6	
MCR	36560	kW

By entering MAN B&W's project guide [40] on K90MC-C6 engines the following data is found:

8K90MC-C6, where:

- '8' stands for the number of cylinders.
- 'K' stands for short stroke.
- '90' stands for the diameter of piston in cm.
- 'M' stands for the engine programme.
- 'C' stands for camshaft controlled.
- 'C' stands for compact engine.
- '6' stands for mark version.

In order to find the correct data for the use in the emission calculation, the lowest possible Specific Fuel Oil Consumption (SFOC) is searched together with its corresponding engine load. The manufacturer mentions then that 'at part load running the lowest SFOC may be obtained at 80% of the optimized power which is equal to 80% of the specified MCR'.

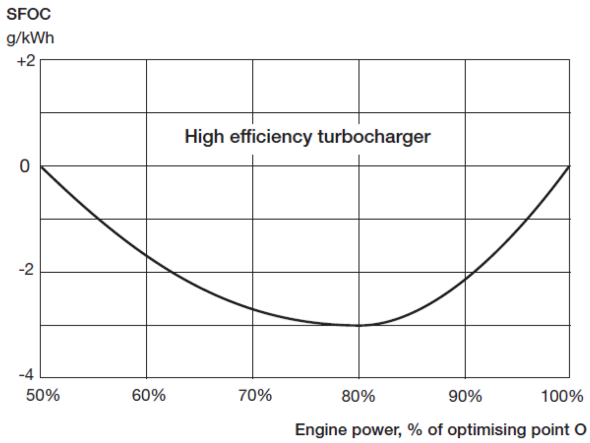
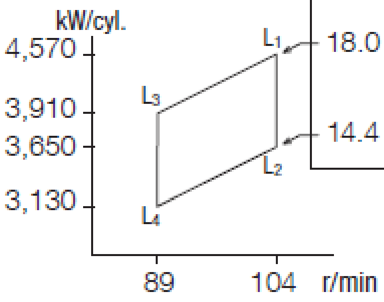


Figure 7 – Graph for the relating the lowest SFOC to the corresponding engine load. In this case the lowest SFOC of 174 g/kWh is at the 80% of EL. Source: [40]

Table 9 - Characteristics of the engine regarding number of cylinders, installed power, SFOC, and rpm. Source: [40]

	Cyl.	L_1 kW
Stroke: 2,300 mm	6	27,420
	7	31,990
	8	36,560
	9	41,130
	10	45,700
	11	50,270
	12	54,840



MEP bar	SFOC g/kWh	
	MCR	Minimum at Part Load
18.0	177	174
14.4	171	168

Table 8 - SFOC at engine load in high efficiency turbochargers. Source: [40]

At load Layout point	Specific fuel oil consumption g/kWH		Lubricating oil consumption	
	With high efficiency turbocharger		System oil Approximate g/kWH	MAN B&W Alpha cylinder lubricator
	100%	80%		
L_1 and L_2	177	174	0.1	0.65
L_3 and L_4	171	168		

Table 10 – Rpm and SFOC values at nominal MCR. Source: [40]

Data at nominel MCR (L_1)			SFOC at nominal MCR (L_1)
			High efficiency TC
Engine	kW	r/min	g/kWh
6 K90MC-C6	27,420	104	177
7 K90MC-C6	31,990		
8 K90MC-C6	36,560		
9 K90MC-C6	41,130		
10 K90MC-C6	45,700		
11 K90MC-C6	50,270		
12 K90MC-C6	54,840		

From the tables above and seeing that the lowest SFOC is obtained from an engine load of 80%, the following data is obtained:

- MCR is confirmed to be 36,560 kW.
- The engine load is 80%.
- The SFOC at an 80% of engine load is 174 g/kWh.
- The nominal revolutions per minute are 104 r/min.

Table 11 – Summary of the port names for the round-trip service route that these ships cover.

ROUTE	
1. Valencia (Spain) – ESVLC	6. Aliaga (Turkey) – TRAGA
2. Tarragona (Spain) – ESTRG	7. Piraeus (Greece) – GRPIE
3. Mersin (Turkey) – TRMER	8. Livorno (Italy) – ITLVN
4. Ashdod (Israel) – ILASH	9. Barcelona (Spain) – ESBCN
5. Haifa (Israel) – ILHFA	10. Valencia (Spain) – ESVLC

Table 12 – Dates of the round-trips considered in the case study.

Case A	Case B	Case C	Case D	Case E
29/01/2020-18/02/2020	30/12/2019-25/01/2020	24/01/2020-11/02/2020	05/01/2020-28/01/2020	04/05/2020-26/05/2020
18/05/2020-09/06/2020		11/5/2020-31/05/2020	27/04/2020-19/05/2020	

The provided data from the ships shows that they use Very Low Sulphur Fuel Oil 0.5% (VLSFO 0.5%) with percentages of Sulphur (S) content between 0.047% and 0.07%, and percentages of Carbon (C) content between 0.855%-0.87%.

2.6.1 Case assumptions

Next, are the assumptions made in order to carry out the study:

- That the route these ships take are monthly and, therefore, the dates in which they travel can correspond for the calculation of a whole month.
- Only the emissions produced from navigation are considered.
- That the content of S is 0.059%.
- That the content of C is 0.86%.
- That the engine load is 80%.

2.6.2 Case result validation

Since this method of emission calculation is based on the first obtention of the fuel consumed per trip, first of all is necessary a validation of the method comparing theFO consumption results based on real data FO consumption obtained from the SIMROUTE emissions module. For this purpose, the FO consumption for both the real data and the obtained using the methodology are presented here in Table 13.

Table 13 – Summary table of the consumption for the round-trip route from ESVLC to ESVLC from the 04/05/2020 to the 26/05/2020. The 4th column shows the difference in percentage of the real emissions.

CASE E	FO Cons. Real	FO Cons. Make_emissions	Difference (%)
ESVLC - ESTRG	7.50	7.60	1.29
ESTRG - TRMER	217.50	208.02	4.36
TRMER- ILASH	33.50	32.50	2.99
ILASH - ILHFA	6.90	3.17	54.04
ILHFA - TRAGA	83.40	85.76	2.83
TRAGA- GRPIR	29.10	30.77	5.74
GRPIR - ITLVN	115.80	121.05	4.53
ITLVN - ESBCN	31.80	28.03	11.86
ESBCN - ESVLC	7.20	9.08	26.04
TOTAL	532.70	525.97	1.26

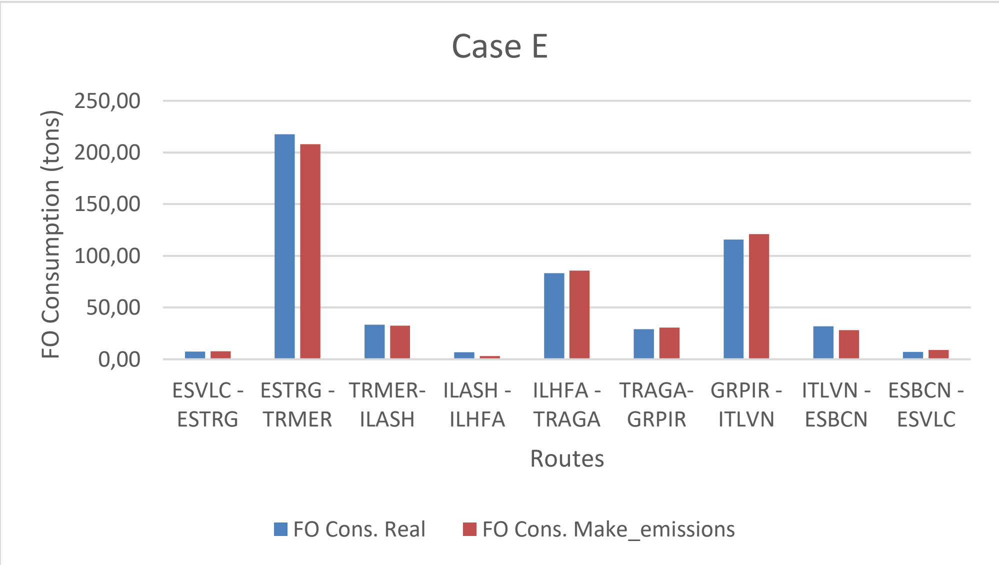
There are some big differences in some routes, such as ESBCN-ESVLC with a 26.04%, ILASH-ILHFA with a 54.04%, and ITLVN-ESBCN with a 11.86%. However, in the overall consumption of the whole trip the difference between the real FO consumed and the calculated using this method is around a 1.26% difference from reality.

The explanation for such differences in specific routes is found in the approximation that the proposed methodology carries out, according to [39] the methodologies neglect the influence of the squat effect and sea currents, and the operations of hotelling and manoeuvrin. But also, the most substantial differences can be observed for low ship speeds.

Table 14 - Average speed table for the routes from the 04/05/2020 to the 26/05/2020. As it can be observed, for very low ship speeds such as the ILASH-ILHFA route, the difference is a 54.04%, and for the routes ITLVN-ESBCN and ESBCN-ESVLC the same phenomenon happens with 11.86% and 26.04% respectively.

ZZC	Average speed (kn)	Difference in consumption (%)
ESVLC - ESTRG	9.38	1.29
ESTRG - TRMER	14.6	4.36
TRMER- ILASH	12.6	2.99
ILASH - ILHFA	7.7	54.04
ILHFA - TRAGA	13.46	2.83
TRAGA- GRPIR	15.6	5.74
GRPIR - ITLVN	13.6	4.53
ITLVN - ESBCN	10.38	11.86
ESBCN - ESVLC	9.25	26.04

Table 15 - Bar graph for the FO Consumption of the real data and the *make_emissions* methodology.



To conclude, an approximate difference of less than 5% (1.26%) is considered acceptable for a calculation of ship FO consumption and, in consequence, the estimation of the respective emissions.

Chapter 3. Results

In this chapter there are the results obtained from the calculation of emissions for the cases presented before. These results will be presented in a route-by-route, month-by-month, and year basis respectively.

3.1.1 Case A1 – 29/01/2020 to 18/02/2020

Table 16 - General tables of the results for Case A1, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the TRMER-ILASH, ILHAS-ILHFA, GRPIE-ITLVN, ITLVN-ESBCN, and ESBCN-ESVLC have average speeds of more than 2 knots below the recommended cruise speed of 17 knots, which may incur slow navigation.

CASE A1			
Route	ESVLC - ESTRG	ESTRG-TRMER	TRMER - ILASH
DATE	29/1/2020	29/1/2020 - 02/02/2020	03/02/2020-04/02/2020
AIS (h)	7.09	88.52	24.38
AIS (miles)	119.03	1659.65	308.97
Average speed AIS (kn)	16.781	18.75	12.67

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	5/2/2020	07/02/2020-09/02/2020	09/02/2020-10/02/2020
AIS (h)	5.22	38.29	9.74
AIS (miles)	71.77	648.09	169.36
Average speed AIS (kn)	13.05	17.2	17.4

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	11/02/2020-14/02/2020	15/02/2020-17/02/2020	17/02/2020-18/02/2020
AIS (h)	68.31	27.67	11.86
AIS (miles)	893.82	377.42	143.91
Average speed AIS (kn)	13.3	13.7	12.4

Table 17 - General tables of the results for Case A1 Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE A1			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	29/1/2020	29/1/2020 - 02/02/2020	03/02/2020-04/02/2020
FO Consumed (Tn)	22.445	395.984	33.213
CO2 (Tn)	70.859	1250.143	104.854
SO2 (Tn)	2.646	46.678	3.915
NOx (Tn)	2.193	38.688	3.245
PM (Tn)	0.049	0.857	0.072

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	5/2/2020	07/02/2020-09/02/2020	09/02/2020-10/02/2020
FO Consumed (Tn)	9.752	133.849	35.043
CO2 (Tn)	30.789	422.570	110.634
SO2 (Tn)	1.150	15.778	4.131
NOx (Tn)	0.953	13.077	3.424
PM (Tn)	0.021	0.290	0.076

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	11/02/2020-14/02/2020	15/02/2020-17/02/2020	17/02/2020-18/02/2020
FO Consumed (Tn)	111.578	47.176	13.170
CO2 (Tn)	352.258	148.938	41.578
SO2 (Tn)	13.153	5.561	1.552
NOx (Tn)	10.901	4.609	1.287
PM (Tn)	0.241	0.102	0.028

Table 18 - Summary table of total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case A1.

CASE A1	**TOTAL**
FO Consumed (Tn)	802.211
CO2 (Tn)	2532.621
SO2 (Tn)	94.562
NOx (Tn)	78.377
PM (Tn)	1.735

3.1.2 Case A2 - 18/05/2020 to 09/06/2020

Table 19 - General table of the results for Case A2, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that all the routes have average speeds of more than 2 knots below the recommended cruise speed of 17 knots, which may incur slow navigation.

CASE A2			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	18/5/2020	19/05/2020-24/05/2020	25/05/2020-26/05/2020
AIS (h)	9.18	128.75	22.50
AIS (miles)	117.40	1662.74	296.11
Average speed AIS (kn)	12.62	12.99	13.12

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	27/5/2020	28/05/2020-31/05/2020	31/05/2020-01/06/2020
AIS (h)	6.89	53.20	17.09
AIS (miles)	73.45	638.05	186.71
Average speed AIS (kn)	11.37	11.85	10.85

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	02/06/2020-05/06/2020	6/6/2020-07/06/2020	08/06/2020-09/06/2020
AIS (h)	74.83	33.51	15.31
AIS (miles)	885.49	380.97	158.16
Average speed AIS (kn)	11.87	11.23	9.28

Table 20 - General table of the results for Case A2 Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE A2			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	18/5/2020	19/05/2020-24/05/2020	25/05/2020-26/05/2020
FO Consumed (Tn)	12.732	191.287	34.419
CO2 (Tn)	40.195	603.904	108.662
SO2 (Tn)	1.501	22.549	4.057
NOx (Tn)	1.244	18.689	3.363
PM (Tn)	0.028	0.414	0.074

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	27/5/2020	28/05/2020-31/05/2020	31/05/2020-01/06/2020
FO Consumed (Tn)	12.458	62.799	16.131
CO2 (Tn)	39.329	198.261	50.926
SO2 (Tn)	1.469	7.403	1.902
NOx (Tn)	1.217	6.136	1.576
PM (Tn)	0.027	0.136	0.035

Route	GRPIE - ITLVN	ITLVN - ESBCN	ESBCN - ESVLC
DATE	02/06/2020-05/06/2020	6/6/2020-07/06/2020	08/06/2020-09/06/2020
FO Consumed (Tn)	85.559	32.675	12.076
CO2 (Tn)	270.114	103.156	38.124
SO2 (Tn)	10.086	3.852	1.424
NOx (Tn)	8.359	3.192	1.180
PM (Tn)	0.185	0.071	0.026

Table 21 - Summary table of the total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case A2.

CASE A2	TOTAL
FO Consumed (Tn)	460.136
CO2 (Tn)	1452.672
SO2 (Tn)	54.240
NOx (Tn)	44.956
PM (Tn)	0.995

3.1.3 Case A - Approximate year emissions

Table 22 - This is an approximate of the year emissions generated by this ship (Case A), in this case, with 2 routes available, make_emissions_yearly.m uses the average emissions between two months to obtain the annual average emissions for this kind of service.

Case A	
FO Consumed (Tn)	7574.078
CO2 (Tn)	23911.760
SO2 (Tn)	892.813
NOx (Tn)	739.996
PM (Tn)	16.384

3.2.1 Case B – 30/12/2019 to 25/01/2020

Table 23 - General table of the results for Case B, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the routes ESVLC-ESTRG, ESTRG-TRMER, TRMER-ILASH, ILHAS-ILHFA, and ESBCN-ESVLC have average speeds of more than 2 knots below the recommended cruise speed of 17 knots, which may incur slow navigation. On the other hand, the other routes do have speeds near the recommended of 17 knots.

CASE B			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	30/12/2019	01/01/2020-05/01/2020	05/01/2020-07/01/2020
AIS (h)	7.85	81.49	23.49
AIS (miles)	104.08	1085.00	256.27
Average speed AIS (kn)	12.50	13.40	11.50

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	10/1/2020	12/01/2020-14/01/2020	15/1/2020
AIS (h)	4.99	34.90	11.09
AIS (miles)	64.54	647.90	176.77
Average speed AIS (kn)	12.90	19.00	16.10

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	16/01/2020-19/01/2020	19/01/2020-22/01/2020	24/01/2020-25/01/2020
AIS (h)	52.92	26.69	15.81
AIS (miles)	884.08	375.84	151.92
Average speed AIS (kn)	17.00	15.50	10.00

Table 24 - General table of the results for Case B Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE B			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	30/12/2019	01/01/2020-05/01/2020	05/01/2020-07/01/2020
FO Consumed (Tn)	10.710	131.597	20.699
CO2 (Tn)	33.811	415.458	65.348
SO2 (Tn)	1.262	15.512	2.440
NOx (Tn)	1.046	12.857	2.022
PM (Tn)	0.023	0.285	0.045

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	10/1/2020	12/01/2020-14/01/2020	15/1/2020
FO Consumed (Tn)	7.282	148.228	29.633
CO2 (Tn)	22.989	467.964	93.551
SO2 (Tn)	0.858	17.473	3.493
NOx (Tn)	0.711	14.482	2.895
PM (Tn)	0.016	0.321	0.064

Route	GRPIE - ITLVN	ITLVN - ESBCN	ESBCN - ESVLC
DATE	16/01/2020-19/01/2020	19/01/2020-22/01/2020	24/01/2020-25/01/2020
FO Consumed (Tn)	166.318	55.910	8.907
CO2 (Tn)	525.076	176.510	28.120
SO2 (Tn)	19.605	6.591	1.050
NOx (Tn)	16.250	5.462	0.870
PM (Tn)	0.360	0.121	0.019

Table 25 - Summary table of FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case B.

CASE B	TOTAL
FO Consumed (Tn)	579.283
CO2 (Tn)	1828.827
SO2 (Tn)	68.284
NOx (Tn)	56.597
PM (Tn)	1.253

3.2.2 Case B – Approximate year emissions

Table 26 - Approximate year emissions generated by Case B. With only one monthly-route available in this case, the average emissions have been obtained by multiplying the route emissions 12 times.

CASE B	
FO Consumed (Tn)	6951.397
CO2 (Tn)	21945.923
SO2 (Tn)	819.413
NOx (Tn)	679.160
PM (Tn)	15.037

3.3.1 Case C4 – 24/01/2020 to 11/02/2020

Table 27 - General table of the results for Case C4, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. This case shows speeds above the 19.6 knots fixed at the beginning of the case study and will be interesting to compare with similar routes and observe the difference in consumption and emissions. On the other hand, at the end of the round-trip there are 3 routes that navigate in slow speeds.

CASE C4			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILHFA**
DATE	24/1/2020	25/01/2020-28/01/2020	29/1/2020
AIS (h)	4.47	72.81	14.51
AIS (miles)	99.51	1548.06	243.31
Average speed AIS (kn)	22.20	21.30	17.30

Route	**ILHFA - TRAGA**	**TRAGA - GRPIE**	**GRPIE - ITLVN**
DATE	31/01/2020-02/02/2020	3/2/2020	04/02/2020-07/02/2020
AIS (h)	35.12	11.95	67.33
AIS (miles)	644.68	176.49	905.62
Average speed AIS (kn)	18.30	14.20	13.90

Route	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	08/02/2020-10/02/2020	10/02/2020-11/02/2020
AIS (h)	33.33	12.54
AIS (miles)	383.44	159.95
Average speed AIS (kn)	11.50	12.90

Table 28 - General table of the results for Case C Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE C4			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILHFA**
DATE	24/1/2020	25/01/2020-28/01/2020	29/1/2020
FO Consumed (Tn)	33.023	474.106	51.261
CO2 (Tn)	104.257	1496.778	161.835
SO2 (Tn)	3.893	55.886	6.043
NOx (Tn)	3.226	46.321	5.008
PM (Tn)	0.071	1.026	0.111

Route	**ILHFA - TRAGA**	**TRAGA - GRPIE**	**GRPIE - ITLVN**
DATE	31/01/2020-02/02/2020	3/2/2020	04/02/2020-07/02/2020
FO Consumed (Tn)	145.508	26.348	129.643
CO2 (Tn)	459.378	83.182	409.290
SO2 (Tn)	17.152	3.106	15.282
NOx (Tn)	14.216	2.574	12.666
PM (Tn)	0.315	0.057	0.280

Route	ITLVN - ESBCN	ESBCN - ESVLC
DATE	08/02/2020-10/02/2020	10/02/2020-11/02/2020
FO Consumed (Tn)	34.093	17.737
CO2 (Tn)	107.632	55.996
SO2 (Tn)	4.019	2.091
NOx (Tn)	3.331	1.733
PM (Tn)	0.074	0.038

Table 29 - Summary table of FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case C.

CASE C4	TOTAL
FO Consumed (Tn)	911.720
CO2 (Tn)	2878.348
SO2 (Tn)	107.471
NOx (Tn)	89.076
PM (Tn)	1.972

3.3.2 Case C5 – 11/05/2020 to 31/05/2020

Table 30 - General table of the results for Case C5, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the majority of the routes have average speeds that may incur slow navigation.

CASE C5			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	11/5/2020	12/05/2020-17/05/2020	18/05/2020-19/05/2020
AIS (h)	9.96	128.75	23.48
AIS (miles)	120.78	1662.74	298.48
Average speed AIS (kn)	12.14	12.99	12.74

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	20/5/2020	21/05/2020-24/05/2020	24/05/2020-25/05/2020
AIS (h)	4.59	48.73	12.49
AIS (miles)	71.40	654.19	179.61
Average speed AIS (kn)	15.54	13.33	14.30

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**
DATE	26/05/2020-29/05/2020	30/05/2020-31/05/2020
AIS (h)	75.42	28.12
AIS (miles)	906.26	331.37
Average speed AIS (kn)	12.05	11.84

Table 31 - General table of the results for Case C5 Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE C5			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	11/5/2020	12/05/2020-17/05/2020	18/05/2020-19/05/2020
FO Consumed (Tn)	12.057	185.792	33.207
CO2 (Tn)	38.064	586.556	104.836
SO2 (Tn)	1.421	21.901	3.914
NOx (Tn)	1.178	18.152	3.244
PM (Tn)	0.026	0.402	0.072

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	20/5/2020	21/05/2020-24/05/2020	24/05/2020-25/05/2020
FO Consumed (Tn)	11.814	81.978	24.950
CO2 (Tn)	37.298	258.808	78.767
SO2 (Tn)	1.393	9.663	2.941
NOx (Tn)	1.154	8.009	2.438
PM (Tn)	0.026	0.177	0.054

Route	GRPIE - ITLVN	ITLVN - ESBCN
DATE	26/05/2020-29/05/2020	30/05/2020-31/05/2020
FO Consumed (Tn)	89.616	31.824
CO2 (Tn)	282.922	100.471
SO2 (Tn)	10.564	3.751
NOx (Tn)	8.756	3.109
PM (Tn)	0.194	0.069

Table 32 - Summary table of the total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case C5.

CASE C5	TOTAL
FO Consumed (Tn)	471.238
CO2 (Tn)	1487.722
SO2 (Tn)	55.548
NOx (Tn)	46.041
PM (Tn)	1.019

3.3.3 Case C5 – Approximate year emissions

Table 33 - Approximated year emissions generated by Case C. With 2 monthly-routes available, *make_emissions_yearly.m* uses the average emissions between two months to obtain the annual average emissions for this kind of service.

CASE C	
FO Consumed (Tn)	8297.748
CO2 (Tn)	26196.424
SO2 (Tn)	978.117
NOx (Tn)	810.700
PM (Tn)	17.950

3.4.1 Case D6 – 05/01/2020 to 28/01/2020

Table 34 - General table of the results for Case D6, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the majority of the routes have average speeds that may incur slow navigation, except for the cases of ILHFA-TRAGA and TRAGA-GRPIE with speeds of 16.60 knots and 20.40 knots respectively.

CASE D6			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	05/01/2020-06/01/2020	07/01/2020-12/01/2020	13/01/2020-14/01/2020
AIS (h)	10.07	114.04	21.66
AIS (miles)	116.45	1642.25	300.85
Average speed AIS (kn)	11.50	14.60	13.20

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	15/1/2020	17/01/2020-19/01/2020	20/1/2020
AIS (h)	6.52	36.51	8.28
AIS (miles)	72.07	615.06	169.36
Average speed AIS (kn)	10.90	16.60	20.40

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	21/02/2020-24/01/2020	25/1/2020-26/01/2020	27/01/2020-28/01/2020
AIS (h)	58.68	30.32	11.14
AIS (miles)	881.32	378.58	155.28
Average speed AIS (kn)	15.10	12.40	13.80

Table 35 - General table of the results for Case D6 Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE D6			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	05/01/2020-06/01/2020	07/01/2020-12/01/2020	13/01/2020-14/01/2020
FO Consumed (Tn)	10.383	238.126	36.552
CO2 (Tn)	32.779	751.776	115.396
SO2 (Tn)	1.224	28.070	4.309
NOx (Tn)	1.014	23.265	3.571
PM (Tn)	0.022	0.515	0.079

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	15/1/2020	17/01/2020-19/01/2020	20/1/2020
FO Consumed (Tn)	6.638	119.915	47.789
CO2 (Tn)	20.956	378.578	150.873
SO2 (Tn)	0.782	14.135	5.633
NOx (Tn)	0.649	11.716	4.669
PM (Tn)	0.014	0.259	0.103

Route	GRPIE - ITLVN	ITLVN - ESBCN	ESBCN - ESVLC
DATE	21/02/2020-24/01/2020	25/1/2020-26/01/2020	27/01/2020-28/01/2020
FO Consumed (Tn)	135.406	39.683	20.617
CO2 (Tn)	427.483	125.281	65.088
SO2 (Tn)	15.961	4.678	2.430
NOx (Tn)	13.229	3.877	2.014
PM (Tn)	0.293	0.086	0.045

Table 36 - Summary table of the total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case D6.

CASE D6	TOTAL
FO Consumed (Tn)	356.819
CO2 (Tn)	1126.494
SO2 (Tn)	33.649
NOx (Tn)	34.862
PM (Tn)	0.772

3.4.2 Case D7 – 27/04/2020 to 19/05/2020

Table 37 - General table of the results for Case D7, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the majority of the routes have average speeds that may incur slow navigation.

CASE D7			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	27/04/2020-28/05/2020	28/04/2020-03/05/2020	04/05/2020-05/05/2020
AIS (h)	8.84	114.99	25.02
AIS (miles)	113.18	1670.05	297.51
Average speed AIS (kn)	13.07	14.58	11.85

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	6/5/2020	08/05/2020-10/05/2020	10/05/2020-11/05/2020
AIS (h)	5.15	48.56	13.15
AIS (miles)	76.37	643.66	187.73
Average speed AIS (kn)	14.25	13.22	14.11

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	12/05/2020-15/05/2020	16/05/2020-17/05/2020	18/05/2020-19/05/2020
AIS (h)	65.81	31.38	13.55
AIS (miles)	896.86	375.70	156.70
Average speed AIS (kn)	13.76	12.16	11.52

Table 38 - General table of the results for Case D7 Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE D7			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	27/04/2020-28/05/2020	28/04/2020-03/05/2020	04/05/2020-05/05/2020
FO Consumed (Tn)	14.280	241.191	28.522
CO2 (Tn)	45.081	761.453	90.045
SO2 (Tn)	1.683	28.431	3.362
NOx (Tn)	1.395	23.565	2.787
PM (Tn)	0.031	0.522	0.062

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	6/5/2020	08/05/2020-10/05/2020	10/05/2020-11/05/2020
FO Consumed (Tn)	15.544	93.681	26.826
CO2 (Tn)	49.073	295.756	84.692
SO2 (Tn)	1.832	11.043	3.162
NOx (Tn)	1.519	9.153	2.621
PM (Tn)	0.034	0.203	0.058

Route	GRPIE - ITLVN	ITLVN - ESBCN	ESBCN - ESVLC
DATE	12/05/2020-15/05/2020	16/05/2020-17/05/2020	18/05/2020-19/05/2020
FO Consumed (Tn)	115.589	37.074	14.309
CO2 (Tn)	364.922	117.044	45.175
SO2 (Tn)	13.625	4.370	1.687
NOx (Tn)	11.293	3.622	1.398
PM (Tn)	0.250	0.080	0.031

Table 39 - Summary table of the total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case D7.

CASE D7	TOTAL
FO Consumed (Tn)	587.016
CO2 (Tn)	1853.240
SO2 (Tn)	69.196
NOx (Tn)	57.352
PM (Tn)	1.270

3.4.3 Case D – Approximate year emissions

Table 40 - Approximated year emissions generated by Case C. With 2 monthly-routes available, make_emissions_yearly.m uses the average emissions between two months to obtain the annual average emissions for this kind of service.

CASE D	
FO Consumed (Tn)	7452.742
CO2 (Tn)	23528.693
SO2 (Tn)	878.510
NOx (Tn)	728.141
PM (Tn)	16.122

3.5.1 Case E – 04/05/2020 to 26/05/2020

Table 41 - General table of the results for Case E, these have been obtained using AIS_route_analysis to obtain the time, distance, and average speed in knots of the journey. Note that the majority of the routes have average speeds that may incur slow navigation.

CASE E			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	04/05/2020-05/05/2020	05/05/2020-10/05/2020	11/05/2020-12/05/2020
AIS (h)	13.16	110.08	23.47
AIS (miles)	121.98	2182.15	295.48
Average speed AIS (kn)	9.18	14.14	12.49

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	13/5/2020	15/05/2020-17/05/2020	17/05/2020-18/05/2020
AIS (h)	10.43	50.48	12.57
AIS (miles)	78.61	654.25	190.03
Average speed AIS (kn)	7.47	12.83	14.87

Route	**GRPIE - ITLVN**	**ITLVN - ESBCN**	**ESBCN - ESVLC**
DATE	19/05/2020-22/05/2020	23/05/2020-24/05/2020	25/5/2020-26/05/2020
AIS (h)	67.63	35.52	17.82
AIS (miles)	909.56	378.34	163.12
Average speed AIS (kn)	13.60	10.56	9.00

Table 42 - General table of the results for Case E Fuel Oil consumption and emissions of CO_2, SO_2, NO_x, and Particulate Matter.

CASE E			
Route	**ESVLC - ESTRG**	**ESTRG-TRMER**	**TRMER - ILASH**
DATE	04/05/2020-05/05/2020	05/05/2020-10/05/2020	11/05/2020-12/05/2020
FO Consumed (Tn)	7.597	208.023	32.497
CO2 (Tn)	23.984	656.739	102.596
SO2 (Tn)	0.896	24.521	3.831
NOx (Tn)	0.742	20.324	3.175
PM (Tn)	0.016	0.450	0.070

Route	**ILASH - ILHFA**	**ILHFA - TRAGA**	**TRAGA - GRPIE**
DATE	13/5/2020	15/05/2020-17/05/2020	17/05/2020-18/05/2020
FO Consumed (Tn)	3.171	85.758	30.771
CO2 (Tn)	10.012	270.742	97.147
SO2 (Tn)	0.374	10.109	3.627
NOx (Tn)	0.310	8.379	3.006
PM (Tn)	0.007	0.186	0.067

Route	GRPIE - ITLVN	ITLVN - ESBCN	ESBCN - ESVLC
DATE	19/05/2020-22/05/2020	23/05/2020-24/05/2020	25/5/2020-26/05/2020
FO Consumed (Tn)	121.045	28.028	9.075
CO2 (Tn)	382.147	88.486	28.651
SO2 (Tn)	14.269	3.304	1.070
NOx (Tn)	11.826	2.738	0.887
PM (Tn)	0.262	0.061	0.020

Table 43 - Summary table of the total FO consumption and emissions of CO_2, SO_2, NO_x, and particulate matter for the Case E.

CASE E	TOTAL
FO Consumed (Tn)	525.966
CO2 (Tn)	1660.502
SO2 (Tn)	61.999
NOx (Tn)	51.388
PM (Tn)	1.138

3.5.2 Case E – Approximate year emissions

Table 44 - Approximate year emissions generated by Case E. With only one monthly-route available in this case, the average emissions have been obtained by multiplying the route emissions 12 times.

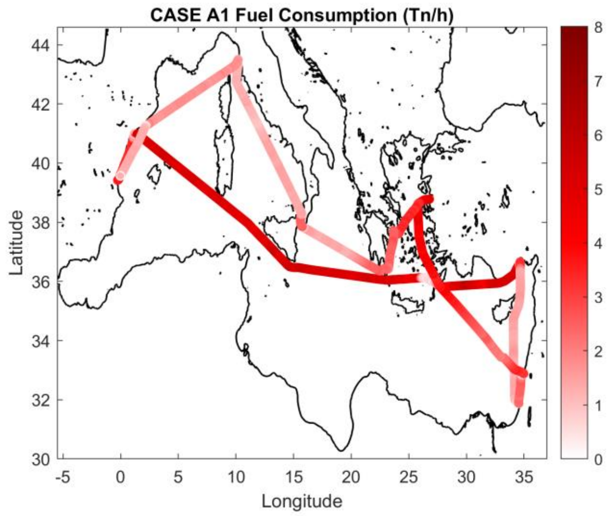
CASE E	
Year emissions	
FO Consumed (Tn)	6311.592
CO2 (Tn)	19926.026
SO2 (Tn)	743.994
NOx (Tn)	616.650
PM (Tn)	13.653

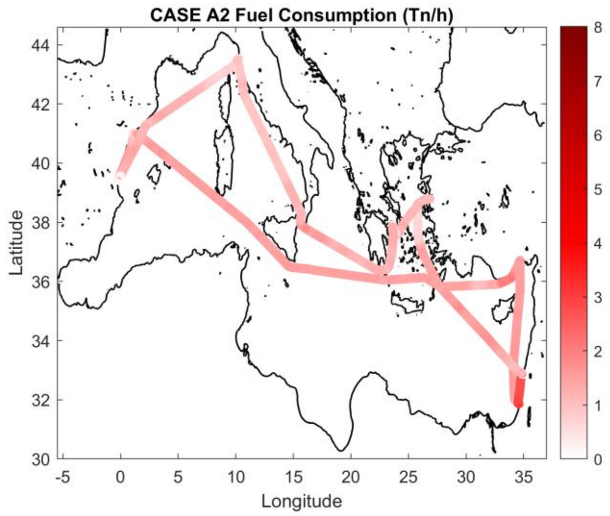
3.6 Case summary

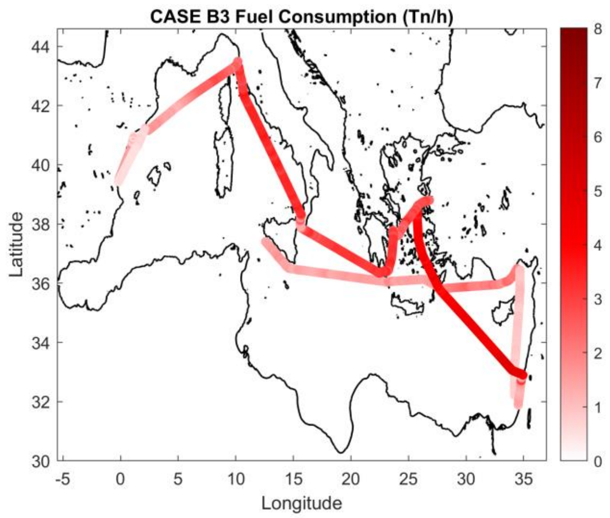
Table 45 – Summary table of the data obtained for every round-trip. Note that there is a difference in distance and hours navigated in some routes, but it does not seem to be the cause for higher consumption.

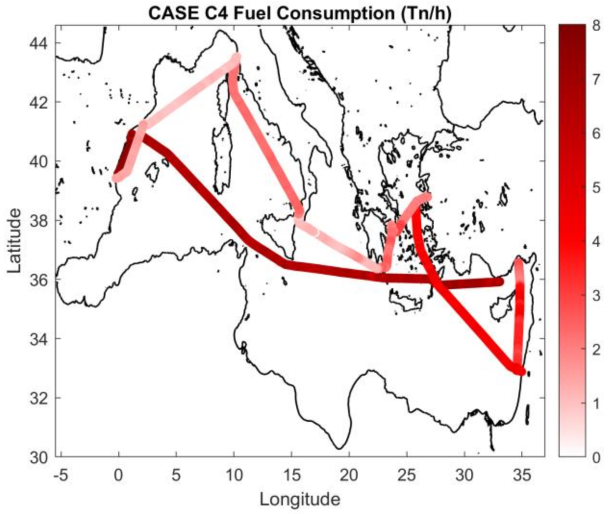
	A1	A2	B	C4	C5	D6	D7	E
AIS (h)	281.08	361.27	259.22	252.05	331.54	297.23	326.45	341.16
AIS (miles)	4392.01	4399.06	3746.40	4161.06	4224.82	4331.23	4417.75	4973.53
Average speed (kn)	15.63	12.18	14.45	16.51	12.74	14.57	13.53	14.58
FO Consumed (Tn)	802.21	460.14	579.28	911.72	471.24	655.11	587.02	525.97
CO2 (Tn)	2532.62	1452.67	1828.83	2878.35	1487.72	2068.21	1853.24	1660.50
SO2 (Tn)	94.56	54.24	68.28	107.47	55.55	77.22	69.20	62.00
NOx (Tn)	78.38	44.96	56.60	89.08	46.04	64.00	57.35	51.39
PM (Tn)	1.74	1.00	1.25	1.97	1.02	1.42	1.27	1.14

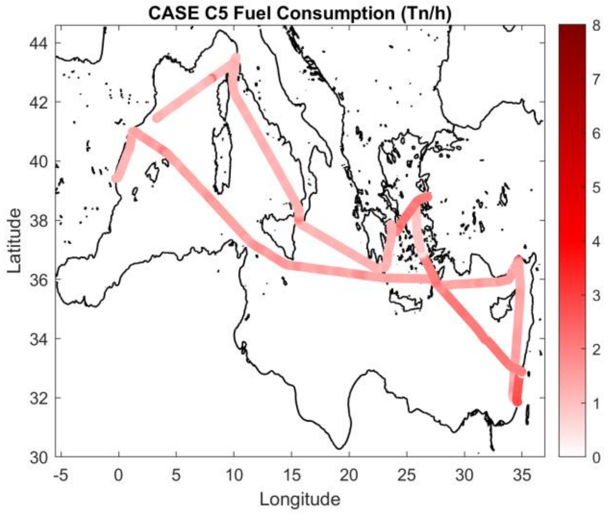
3.6 Case emission and consumption figures

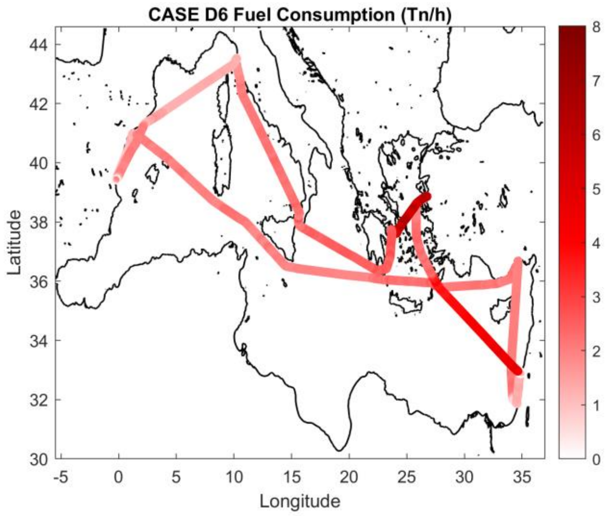


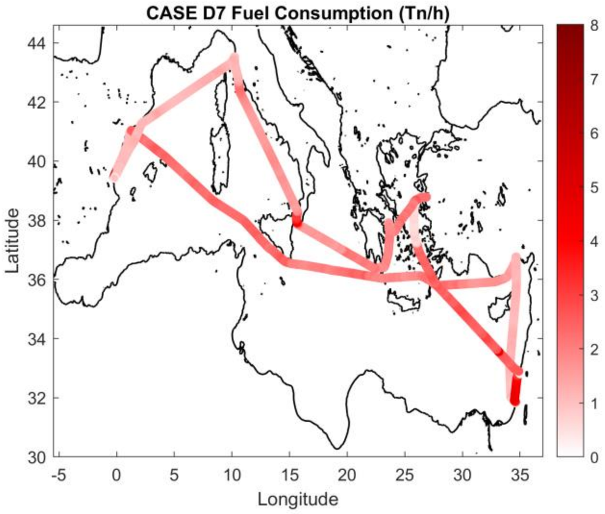





CASE C4 Fuel Consumption (Tn/h)
Latitude
Longitude


CASE C5 Fuel Consumption (Tn/h)
Latitude
Longitude


CASE D6 Fuel Consumption (Tn/h)
Latitude
Longitude



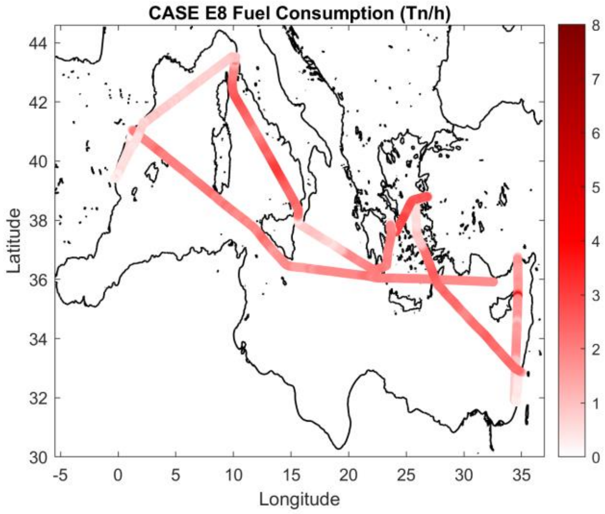
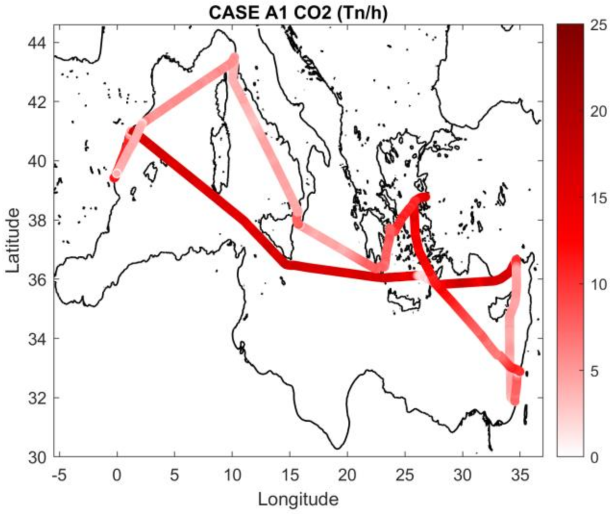


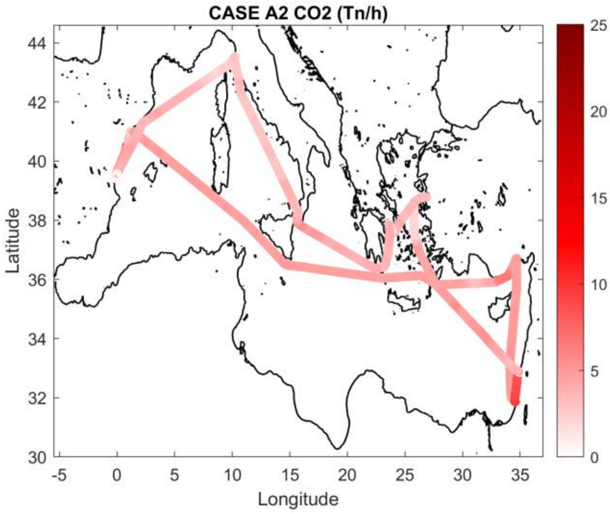
Figure 8 - These figures have been obtained using the make_emissions_map.m module which plots the rate of consumption for the different waypoints of the routes. The figures are ordered from A1 to E8 and show the rates of consumption for every round-trip in the case study.

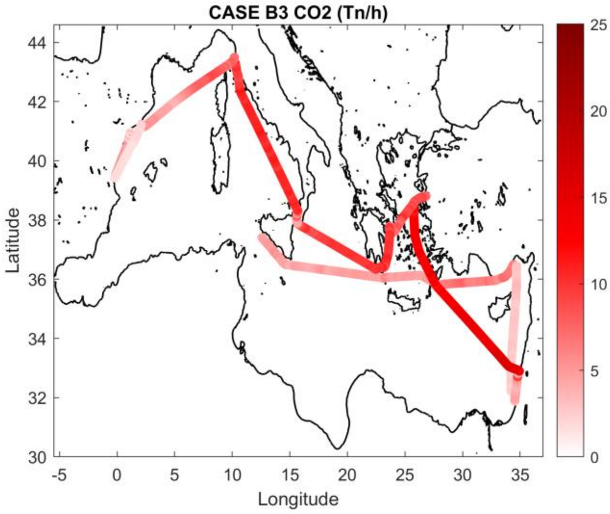
First of all, case A1, B3, and C4 have been found to be the cases with higher emission rates with rates of around 8 tons/h of FO consumed in C4 for the routes of ESVLC-ESTRG and ESTRG-TRMER, but also in A1 with rates of 5-6 tons/h in ESTRG-TRMER and 3-4 tons/h in ILHFA-TRAGA. In addition, case B3 shows a high and sustained consumption rate for long distance routes such as ILHFA-TRAGA, TRAGA-GRPIE, and GRPIE-ITLVN.

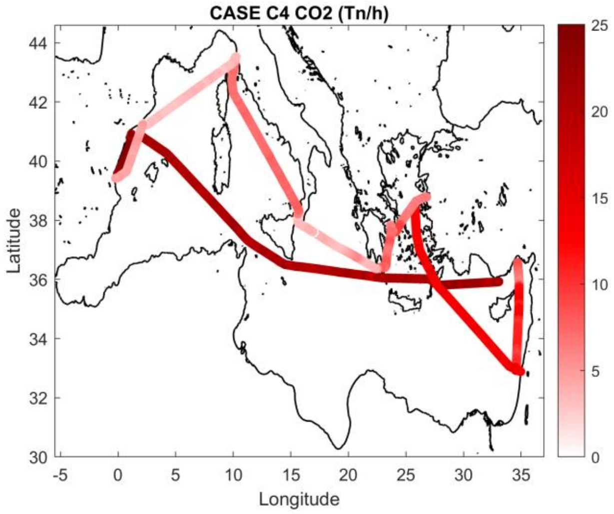
Secondly, in contrast with the high emission cases, cases A2 and C5 have been found to be the ones with the lowest consumption rates and, thus, with the lowest emissions. The whiter colours show that overall the consumption rate values range 1-3 tons/h of FO.

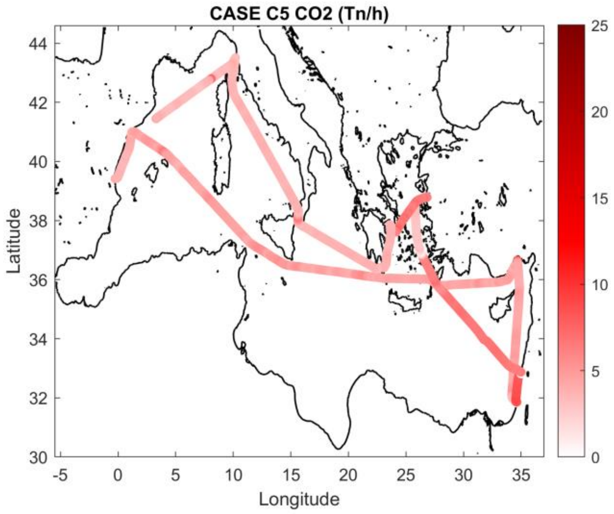
Finally, cases D6, D7, and E8 are observed to be in the middle of consumption rates, with some routes with low consumption but mid values overall of around 2-4 tons/h of FO.

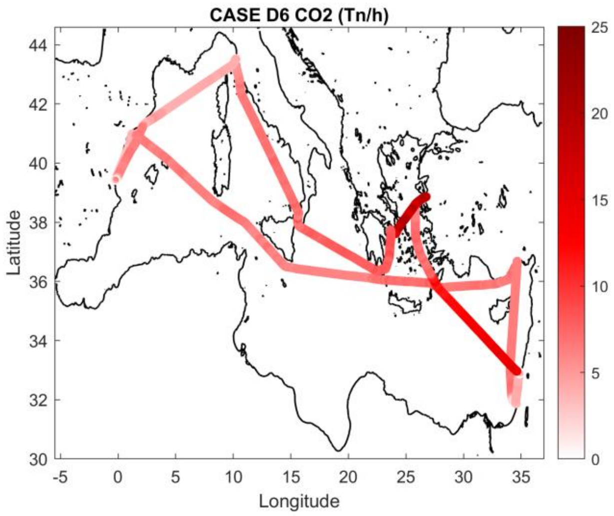

CASE A1 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0

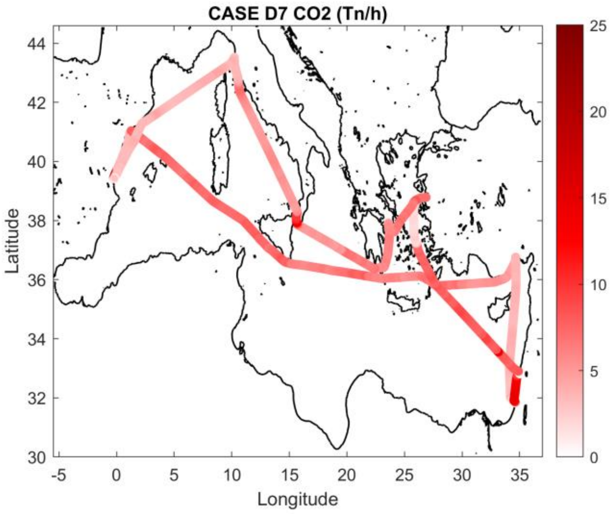

CASE A2 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0


CASE B3 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0


CASE C4 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0


CASE C5 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0


CASE D6 CO2 (Tn/h)
Latitude
Longitude
44
42
40
38
36
34
32
30
-5
0
5
10
15
20
25
30
35
25
20
15
10
5
0



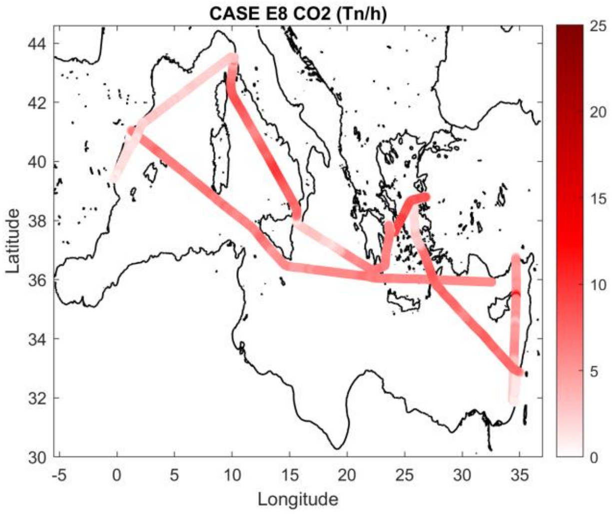


Figure 9 – These figures represent the rate of CO_2 emission for the different waypoints of the routes. The figures are ordered from A1 to E8 and show every round-trip in the case study.

The most CO_2 emitters have been found to be C4, A1, and B3 with up to 25 tonnes/h, 20 tonnes/h, and 15 tonnes/h, respectively, for sustained periods of time.

On the other hand, the least CO_2 emitter cases were A2, C5, D7 and E8 with emissions mostly under 10 tonnes/h and even up to 5 tonnes/h for cases A2 and C5.

Chapter 4. Discussion

4.1 Case A

With a consumption of 460.136 tons (A2) and 802.211 tons (A1), there is a special difference due to the differences in average speed, which also translate into higher emissions of CO_2 (1452.67 – 2532.62 tons), SO_2 (54.24 – 94.56 tons), NO_x (44.96 – 78.38 tons), and particulate matter (1.00 – 1.74 tons).

4.2 Case B

To continue, case B has a higher consumption than A2, even though the distance and time sailed are lower, the average speed has a huge influence with a total final consumption of 579.28 tons of FO compared to the 460.136 tons of A2.

By observing the case emission and consumption figures, it can be noticed that whereas the ESTRG-TRMER route in A2 has a higher hourly consumption/emission rate, case B shows a more sustained and high consumption rate for the routes of ILHFA-TRAGA, and GRPIE-ITLVN, which translates into the following emissions CO_2 (1828.83 tons), SO_2 (68.28 tons), NO_x (56.60 tons), and particulate matter (1.25 tons).

4.3 Case C

As for cases C4 and C5, they both show a big difference in average speeds (particularly 4 knots). This once again shows the influence of the increase in speed in the obtainment of FO consumption and emissions.

Specifically, case C4 is the round-trip/example with the highest consumption and emissions of the case study, with total numbers of 911.72 tons of FO consumed, 2878.35 tons of CO_2, 107.47 tons of SO_2, 89.08 tons of NO_x, and 1.97 tons of particulate matter.

From another point of view, this is also observed in the emission rate figures with the longest and highest sustained emissions for any case, for instance, ESTRG-TRMER route maintains a rate of about 7 to 8 tons an hour of FO consumption.

4.4 Case D

In the fourth place, case D is composed by case D6 and D7 and have middle rates of emissions. With average speeds of 14.57 and 13.53 knots respectively they show rates higher than cases A2 and C5.

The values found in the summary table position them below case A1 with 655.11 tons of FO (D6), and 587.02 tons (D7), the rest of emission values are: 2068.21 tons and 1853.24 tons of CO_2, 77.22 tons and 69.20 tons of SO_2, 64.00 tons and 57.35 tons of NO_x, and 1.42 tons and 1.27 tons of particulate matter.

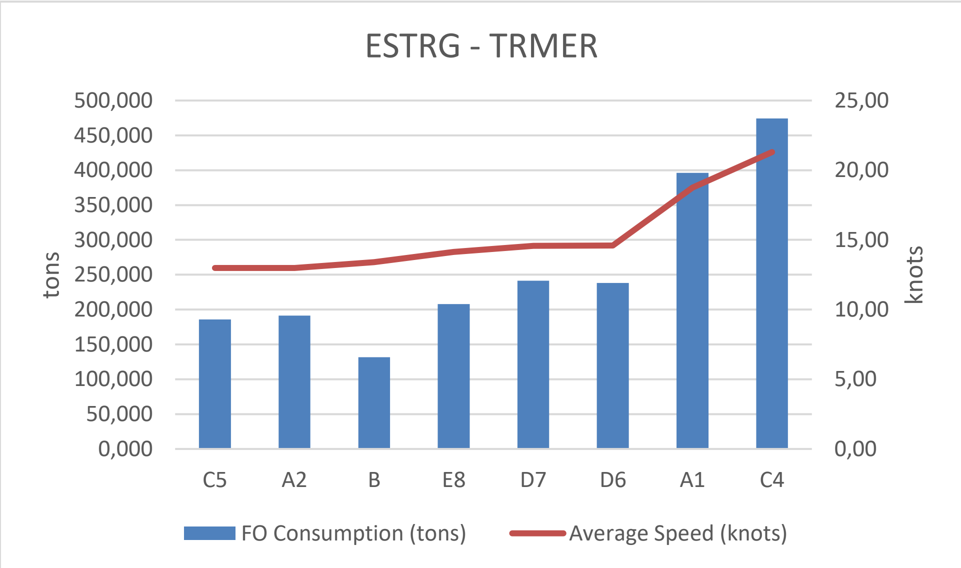
4.5 Case E

Finally, case E with an average speed above the overall average of the routes but still below cases A1, C4, B3, D6, and D7 in terms of FO consumption and emissions. This is due to the fact that only linking the average speed to the increase of emissions is wrong as it is the consumption and emission rates, thus the instantaneous speed, that have a major influence of what reality ends up being. For example, in some routes of case E the average speed is quite low with values between 7-9 knots in ILASH-TRAGA, ESVLC-ESTRG, and ESBCN-ESVLC, whereas it is the influence of high rate of emissions in the long routes that ends up increasing the quantity emitted in the end. If the figure FIGURE NUMBER from E7 at 3.6 Section is observed, the higher rates of emissions are located in the beginning of ESTRG-TRMER and along the coast of Italy and Greece.

To summarize, case E ends up with total numbers of 525.97 tons of FO consumed, 1660.50 tons of emitted CO_2, 62.00 tons of SO_2, 51.39 tons of NO_x, and 1.14 tons of particulate matter.

4.7 Ship speed and consumption/emission rates

Table 27 - This graph shows the fuel consumption and average speeds of every case for the route from Tarragona to Mersin and it is very useful to see the influence of the formula for transient power used in the obtention of fuel consumption and emission of pollutants.



$P_{transient} = kv^3$ *Equation 15*

$k = \frac{\varepsilon_p \cdot P_{installed}}{(V_{design})^3}$ *Equation 16*

For both factors of the *equation 17* formula, the instantaneous speed applied plays a very important role since it is a cubed factor, therefore, the variation of the power obtained using this approximation is highly dependent on this data. However, it is necessary to point out that this poses one of the limitations of the methodology because since the speed obtained through AIS data is the Speed Over Ground (SOG) of the ship, it does not manifest the influence of the weather on the ship and, thus, on the engine load. That would give wrong estimations for those cases in which the ship has a higher engine load in order to maintain a certain speed value during a wave episode, or just when affected by sea currents. The best solution would be to have access to the engine load values for every speed that the ship is developing but since this kind of data is not easily obtained, the definition of new engine load and specific fuel oil consumption relative values can be done to introduce better approximations.

Another phenomenon observed in this case study is sslow, that is a consequence of the introduction of the maximum Sulphur content allowed in the fuel used by ships. This limit, as stated before in the introduction section, has been reduced to 0.1% in the Emission Control Areas (ECAs) from 1 January 2015, and, more recently, to 0.5% for those areas not in ECAs from 2020. According to [41] the compliance with the sulphur regulation was predicted to negatively affect the competitiveness of short sea shipping (SSS) by substantially increasing operating costs.

'To comply with the 0.1 percent Sulphur regulation, shipping companies were faced with a number of possible solutions. They could switch from traditional heavy fuel oil (HFO) to distillate fuel (marine gas oil or ultra-low Sulphur fuel), having a maximum Sulphur content of 0.1%. Another option was to install after-treatment technologies (e.g. scrubbers) on board, or convert the vessels to use alternative fuels such as liquid natural gas (LNG), methanol or biofuels. The required extensive costs for retrofitting the vessels, the immature technology and the price uncertainty for alternative fuels have made the proposed solutions unattractive for a number of shipping companies.'

Sslow has appeared as a way of reducing emissions by reducing vessel's speed, or even maintaining financially feasible a service route with no direct increase of short-term operating costs. However, sslow does result in an increase in transit time and delays to cargo delivery which, in some cases, may translate into the deployment of more or larger ships to be able to meet former schedules of services and not loose competitiveness against road-transport.

In this case study, sslow can be observed with the *make_emissions_map.m* module, which shows the consumption and emission hourly rates for every route used. In cases A2, C5, D7, and E8 this phenomenon is largely present, seeing rates of very low hourly consumption. As it is the case of the ship, most of the routes are already below the design speed of around 20 knots defined at the beginning of the study. Actually, the FO used is Very Low Sulphur FO which may explain why the company has decided to reduce the consumption of the ships and be able to maintain operative costs at a feasible level.

4.7 Tools introduced as emission estimation method in SIMROUTE

As part the development of the project, the most important objective of this work was to provide new tools that would introduce the emission evaluation methodologies to SIMROUTE and make them available for other students and researchers. Therefore, the most important thing was to provide with the necessary information and steps to analyze real cases of ship emissions.

4.7.1. monthly_route.m module

This module has been created in order to group routes from AIS. Having to do a significant amount of measures can be very time consuming and, therefore, this tool is found useful because it groups any amount of route *.csv* files into a single *.mat* file. Even though, it is called 'monthly_routes' it can also be used to create packages of weekly or annual routes.

4.7.2. make_emissions_yearly.m module

In order to use the recent ability of SIMROUTE to use AIS files in the form of *.csv* files, this module opens a new path to fulfil the main objective of the present paper, which is to allow the user to obtain approximate calculations of the annual emissions of a ship. However, it also has other functions, as it uses route packages obtained from the previous module (*monthly_route.m*) it can be used to evaluate the emissions of a group of similar ships using just a single package with all the routes. This is an advantage for future studies but it can also be its downside, if there are multiple, and different, ships to be studied at the same time, the module would need as inputs new packages with the required information regarding ship and engine characteristics, which, at the moment, would need to be done in separate packages and introducing the information manually.

All in all, it serves as a time saving tool for large-scale calculations of emissions, and with an appropriate amount of 'monthly' packages that compose a representative part of the annual routes of a ship it can be a quite accurate method of annual emission estimation. In fact, the AIS data is a very accurate source of information of the ship traffic and the location and speed values of the ships, with a properly developed methodology of emission estimation, this AIS emission methodology can evolve into a reliable source of information for emission control in the future.

4.7.3. make_emissions_map.m module

Finally, the calculation of emissions is not the only way of how pollution can be evaluated, there are other questions to this matter that are where and how these emissions have been produced. As a first step towards emission distribution evaluation, *make_emissions_map.m* creates figures of the area studied with the routes introduced, and plots the rates of consumption for each waypoint in the AIS data. As a specific objective of the project, this tool allows the user to locate those areas with higher emissions and even evaluate phenomena such as sslow. In fact, the case study presented above has shown that sslow is real and that it may have many causes but is mainly due to the increase of operation costs from the direct influence of the new emission measures adopted.

This tool may prove useful in future works, by providing a distribution study of the emissions produced in a gridded area. For instance, it would be possible to assign a grid to a local area and obtain the allocation of those areas with higher emissions and quantify them by only using data from an easily-accessed source such as the Automatic Identification System.

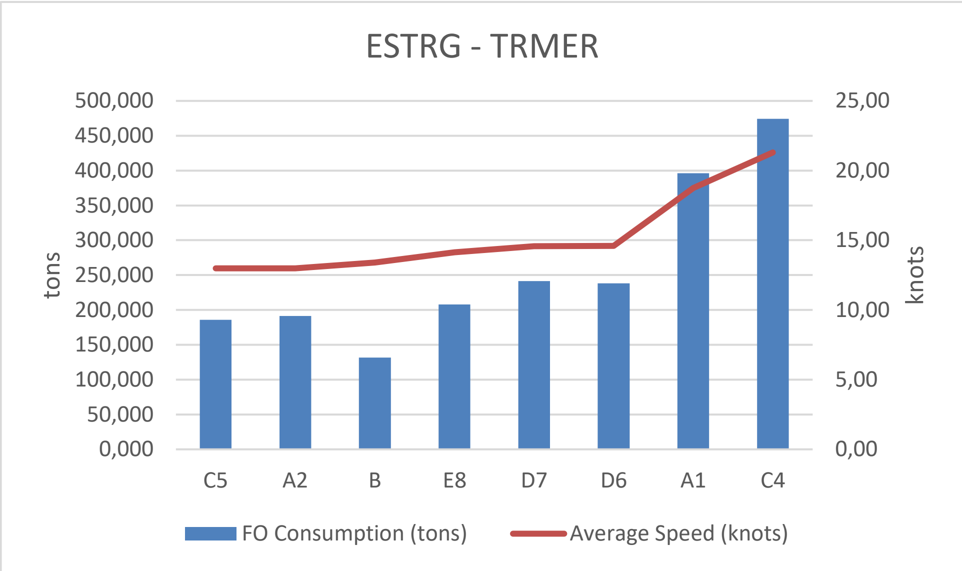
Chapter 5. Conclusions

In this project, a first approach has been made to the introduction of new uses to the available SIMROUTE software. The previous introduction of AIS data use into SIMROUTE proves as a useful tool for many areas of study. More specifically, new modules for the evaluation of pollutants have been introduced inspired by the current emission evaluation module for optimum routes. As a result, now it is possible to estimate the emissions for real routes from AIS, group these routes into packages and obtain the emissions of ships, and even calculate an approximate value for ship annual emissions. In addition, there has been the creation of another short script that plots the hourly rate of fuel oil consumption and emission of pollutants in a map, and allowing the user to observe and study those areas of special interest for the emissions of a route. Finally, in order to make these new additions accessible for other interested students or researchers, a short guide is presented on how to use them for the purpose of emission studies.

In parallel to all the new introductions explained here, there has been a case study carried out to evaluate the calculations of the method included. To summarize the discussions chapter, the case study firstly uses real data of fuel oil consumption for one of the cases to observe the differences to AIS obtained data, and the results have been validated. Secondly, having validated the methodology, a total of five cases have been used to calculate their corresponding fuel oil consumption and emission of pollutants. The available data has covered routes from the 30/12/2020 to 18/02/2020 and from 27/04/2020 to 09/06/2020 in the area of the Mediterranean for a set of twin ships that cover the same route. The technical data for AIS routes, ship engine details and fuel oil composition have been obtained through a fellow student who is studying other phenomena related to fuel consumption but has asked to keep the source confidential. In total 70 routes have been used to obtain their emissions, and year estimates have been calculated.

This case study has shown the different aspects to consider for the calculation of emissions. First of all, the availability of data which for the purpose of emission calculation can be scarce. It can be impossible sometimes to recover direct information from shipowners as not many will provide such information from their ship engines and fuel usage. Therefore, in order to develop an emission calculation software further there should be an agreement between two parties to carry out an exchange of data in order to validate and evaluate the progress of such software. Secondly, the required level of accuracy of the study, since it will vary depending on whether the calculations have been done for a whole year or just a representative period. Thirdly, that sslow could be one of the weaknesses of the STEAM methodology because according to it, most of the discrepancies come with very low speeds which, in fact, the validation of results at the beginning of the case study showed differences of 10% to 50% in those slow speed journeys. Finally, that these tools could be used for the observation of fuel consumption savings when comparing AIS routes and optimum routes obtained using SIMROUTE's weather ship routing software.

Table 28 – Fuel oil consumption versus average speed graph for the route Tarragona to Mersin.



As seen in the discussions section, this graph has shown the importance of speed in the increase of consumption of a vessel. For cases with average speeds around 10 knots the fuel consumption values have stayed below 250 tons in the route from Tarragona (Spain) to Mersin (Turkey). However, when increasing the speed for the same route to values of 18 knots or 21 the fuel consumption increases rapidly to levels of 400-450 tons. Actually, the use of the newly added tools have allowed to observe the consequences of the new regulations being adopted regarding the composition of ship fuels. In this case, from 2020 these ships have been affected by the new amendments to MARPOL's Annex VI, with the introduction of the sulphur content cap to 0.5% in fuel oils. Consequently, there has been a switch to VLSFO that, in an atmosphere of economic uncertainty and the lack of acceptable technology for the refitting of the ships, has provoked an aim to maintain operative costs in low levels, thus, the appearance of sslow as a method of reducing speeds to reduce fuel consumption.

To conclude, as suggestions for future advancements, the introduction of methodology for the calculation of the consumption and emissions produced by the hotelling and manoeuvring of ships into SIMROUTE would improve the software largely, adding significant meaning to future analysis. Moreover, it would be interesting to see the use of these new tools to evaluate the savings obtained from optimum routes and actually observe the advantages of maintaining a certain speed and a recommended engine load for low consumption. This could mean that SIMROUTE would have been proved to be a useful tool not only for sailing time reduction but for fuel efficiency too. On the other hand, the availability of the FNB's AIS station is appealing for future studies of the emissions produced in the area surrounding Barcelona's coast. In other words, by creating a grid structure of the coast and using AIS data, an emission study could be carried out which would obtain the concentration of pollutants in the air. CO_2

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Annex 1. Monthly_routes.m

```
clear all
close all
clc
tic

%% MONTHLY ROUTES
%This code will group a given number of routes introduced in .csv files
%with the variables of Timestamp, Speed, Course, Latitude and Longitude and
%will produce a .mat file containing all of them with interpolated
%waypoints.

%%% USER INPUT
dir_arx='in/';
arxiu_out='month4'; % Name of the output file
ARX={'0501_0601.csv','0701_1201.csv','1301_1401.csv','1501.csv','1701_1901.cs
v','2001.csv','2101_2401.csv','2501_2601.csv','2701_2801.csv'};

%%% END OF USER INPUT

n=length(ARX);

filename=[dir_arx ARX{1}];

FILE=readtable(filename);
warning('off','last')

t=datenum(FILE.x_Timestamp(end)-FILE.x_Timestamp(1)).*24; %Calculate time of
the trip in hours
FILE.x_Timestamp=datenum((FILE.x_Timestamp(:)-FILE.x_Timestamp(1)).*24);

route=[FILE.x_Timestamp,FILE.Speed,FILE.Course,FILE.Latitude,FILE.Longitude];

xx=(0:0.05:t)';

route=[xx,interp1(FILE.x_Timestamp,FILE.Speed,xx,'linear'),interp1(FILE.x_Tim
estamp,FILE.Course,xx,'linear'),interp1(FILE.x_Timestamp,FILE.Latitude,xx,'li
near'),interp1(FILE.x_Timestamp,FILE.Longitude,xx,'linear')];

whole=route;
Month.route1=route;
Timestamp=route(end,1);
Speed=route(:,2);

a=0;
for a=2:1:n;

    filename=[dir_arx ARX{a}];

    FILE=readtable(filename);
    warning('off','last')
```

```
    t=datenum(FILE.x_Timestamp(end)-FILE.x_Timestamp(1)).*24; %Calculate time
of the trip in hours
    FILE.x_Timestamp=datenum((FILE.x_Timestamp(:)-FILE.x_Timestamp(1)).*24);


route=[FILE.x_Timestamp,FILE.Speed,FILE.Course,FILE.Latitude,FILE.Longitude];


    xx=(0:0.05:t)';


route=[xx,interp1(FILE.x_Timestamp,FILE.Speed,xx,'linear'),interp1(FILE.x_Tim
estamp,FILE.Course,xx,'linear'),interp1(FILE.x_Timestamp,FILE.Latitude,xx,'li
near'),interp1(FILE.x_Timestamp,FILE.Longitude,xx,'linear')];

    fname = ['route',num2str(a)];
    Month.(fname) = route;

    whole=[whole;route];
    Speed=[Speed;route(:,2)];

    Timestamp=Timestamp+route(end,1);

end


save([dir_arx arxiu_out],'Month','Timestamp','Speed','n')
toc
```

Annex 2. Make_emissions_yearly.m

```
clear all,clc,close all

%% MAKE ANNUAL EMISSIONS
%This code will calculate the emissions for multiple routes grouped in
%packages creates with monthly_routes.m module. The outputs will be the
%emission for each route and the total emissions for each package
%(considered as a month). Finally, it will approximate the annual emissions
%of the case by obtaining the average monthly emissions.

%%% USER INPUT
ARX={'month1.mat','month2.mat'}; %load AIS route packages from
monthly_routes.m
dir_arx='in/';

%%%Ship engine and fuel data

EL=0.80;%Engine load (in unit percentage)
Pow_Ins=36560;%Engine Power(kW)
V_design=19.6;%Design speed (knots)
SFOC=174; %Specific fuel compsuntion (gr/kWh).
SC=0.059; %Sulphur content of fuel (mass%) for Fuel Oil
CC=0.86; %Carbon content of fuel (mass %)
Engine_RPM=104; % Engine rpm

M_S=32.0655; %Molar mass of sulphur (gr/mol)
M_SO2=64.06436; % molar mass of sulphur dioxide g/mol (number of mols of
S=number of mols of SO2)
M_C=12.01; %Molar mass of carbon (gr/mol)
M_CO2=44.0886; %Molar mass of carbon dioxide (gr/mol) (number of mols of
C=number of mols of CO2)

%%PARTICULATE MATTER%

EF_EC=0.08; %Emission factor elementary carbon (gr/kWh)
EF_OC=0.2; % Emission factor for organic carbon (gr/kWh)
EF_ASH=0.06; %Emission factor for ash (gr/kWh)
OC_EL=1.024; %Part of organic carbon dependent of EL (dimensionless)

%%%%% END OF INPUT

%%%%
j=length(ARX);
if j>12
    disp('Please, only 12 files maximum.')
    return
end
if j<1
    disp('Please, enter at least a month file.')
    return
end

b=0;
```

```
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)]


    a=0;
    for a=1:AIS.n

        rname = ['route',num2str(a)]
        AIS.Month.(rname);

        cte_k=(EL*Pow_Ins)/(V_design)^3;%Constant K (kW/kn^3)

        Pow_trans_h_AIS=cte_k*(AIS.Month.(rname)(:,2)).^3;%hourly transitient
Power (kW)


Pow_trans_AIS=sum(Pow_trans_h_AIS(1:end))/(length(Pow_trans_h_AIS));%Transiti
ent Power

        Fuel_comp_AIS=Pow_trans_AIS*SFOC*AIS.Month.(rname)(end,1) ;%gr

        disp(['Fuel consumption has been: ' num2str(Fuel_comp_AIS/.10^(-06))
' Tn'])
        disp([' '])

        %%% SO2
        n_SO2=(SFOC*SC)/M_S;% number of mols of sulphur dioxide
        Emi_fac_SO2=M_SO2*n_SO2; % SO2 Emission factor gr/kWh

        SO2_AIS=AIS.Month.(rname)(end,1)*Pow_trans_AIS*Emi_fac_SO2;

        %%% CO2
        n_CO2=(SFOC*CC)/M_C;% number of mols of carbon dioxide
        Emi_fac_CO2=M_CO2*n_CO2; % CO2 Emission factor gr/kWh

        CO2_AIS=AIS.Month.(rname)(end,1)*Pow_trans_AIS*Emi_fac_CO2;

        %%% NOX
        %Emi_fac_NOx=45*Engine_RPM^(-0.2); %NOx emission factor gr/kWh

        if Engine_RPM<130;
            Emi_fac_NOx=17;
        else
            if (130<=Engine_RPM)&&(Engine_RPM<=2000);
                Emi_fac_NOx=45*Engine_RPM^(-0.2);
            else
                if Engine_RPM>2000;
                    Emi_fac_NOx=9.8;
                end
            end

        end

        NOx_AIS=AIS.Month.(rname)(end,1)*Pow_trans_AIS*Emi_fac_NOx;
```

```
        %%% PARTICULATE MATTER

        EF_SO4=0.312*SC; % Emission factor for SO4 (gr/kWh)
        EF_H2O=0.244*SC; % Emission factor H2O (gr/kWh)

        SFOC_REL=(0.445*EL^2)-(0.71*EL)+1.28; %(Specific fuel oil consumption
- Relative)

        Emi_fac_PM=SFOC_REL*(EF_SO4+EF_H2O+EF_OC*OC_EL+EF_EC+EF_ASH);
%Particulate matter emission factor (gr/kWh)

        PM_AIS=AIS.Month.(rname)(end,1)*Pow_trans_AIS*Emi_fac_PM;  %
Particulate matter emitted in gr AIS route

        ME.(mname).(rname).FC=Fuel_comp_AIS/.10^(-06); %in Tons
        ME.(mname).(rname).CO2=CO2_AIS/.10^(-06); %in Tons
        ME.(mname).(rname).SO2=SO2_AIS/.10^(-06); %in Tons
        ME.(mname).(rname).NOx=NOx_AIS/.10^(-06); %in Tons
        ME.(mname).(rname).PM=PM_AIS/.10^(-06); %in Tons

        disp(['CO2 have been: ' num2str(CO2_AIS/.10^(-06)) ' Tn'])
        disp([' '])

        disp(['SO2 have been: ' num2str(SO2_AIS/.10^(-06)) ' Tn'])
        disp([' '])

        disp(['NOx have been: ' num2str(NOx_AIS/.10^(-06)) ' Tn'])
        disp([' '])

        disp(['PM have been: ' num2str(PM_AIS/.10^(-06)) ' Tn'])
        disp([' '])
        disp([' '])
    end
end


b=0;
for b=1:j
    filename=[dir_arx ARX{b}];
    AIS=load(filename);

    mname = ['month',num2str(b)];

    ME.(mname).total.FC=0;
    ME.(mname).total.CO2=0;
    ME.(mname).total.SO2=0;
    ME.(mname).total.NOx=0;
    ME.(mname).total.PM=0;

    a=0;
    for a=1:AIS.n
        rname = ['route',num2str(a)];
        ME.(mname).total.FC=ME.(mname).total.FC+ME.(mname).(rname).FC;
        ME.(mname).total.CO2=ME.(mname).total.CO2+ME.(mname).(rname).CO2;
        ME.(mname).total.SO2=ME.(mname).total.SO2+ME.(mname).(rname).SO2;
```

```
        ME.(mname).total.NOx=ME.(mname).total.NOx+ME.(mname).(rname).NOx;
        ME.(mname).total.PM=ME.(mname).total.PM+ME.(mname).(rname).PM;

    end

    disp(['Month ' num2str(b) ' fuel consumption has been: '
num2str(ME.(mname).total.FC) ' Tn'])
    disp([' '])
    disp(['         CO2 emissions have been: ' num2str(ME.(mname).total.CO2) '
Tn'])
    disp([' '])
    disp(['         SO2 emissions have been: ' num2str(ME.(mname).total.SO2) '
Tn'])
    disp([' '])
    disp(['         NOx emissions have been: ' num2str(ME.(mname).total.NOx) '
Tn'])
    disp([' '])
    disp(['         PM emissions have been: ' num2str(ME.(mname).total.PM) '
Tn'])
    disp([' '])
end

%Year approximation

ME.year.FC=0;
ME.year.CO2=0;
ME.year.SO2=0;
ME.year.NOx=0;
ME.year.PM=0;

for b=1:j
    mname = ['month',num2str(b)];
    ME.year.FC=ME.year.FC+ME.(mname).total.FC;
    ME.year.CO2=ME.year.CO2+ME.(mname).total.CO2;
    ME.year.SO2=ME.year.SO2+ME.(mname).total.SO2;
    ME.year.NOx=ME.year.NOx+ME.(mname).total.NOx;
    ME.year.PM=ME.year.PM+ME.(mname).total.PM;
end

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];

    EMEP.(mname).NOx=AIS.Timestamp*(Pow_Ins*NOx_EF)/.10^(-06);
    EMEP.(mname).PM=AIS.Timestamp*(Pow_Ins*PM_EF)/.10^(-06);

end

if j<12

ME.year.FC=ME.year.FC/j*12;
ME.year.CO2=ME.year.CO2/j*12;
ME.year.SO2=ME.year.SO2/j*12;
ME.year.NOx=ME.year.NOx/j*12;
ME.year.PM=ME.year.PM/j*12;
```

```
end

disp(['Year fuel consumption has been: ' num2str(ME.year.FC) ' Tn'])
disp([' '])
disp(['     CO2 emissions have been: ' num2str(ME.year.CO2) ' Tn'])
disp([' '])
disp(['     SO2 emissions have been: ' num2str(ME.year.SO2) ' Tn'])
disp([' '])
disp(['     NOx emissions have been: ' num2str(ME.year.NOx) ' Tn'])
disp([' '])
disp(['     PM emissions have been: ' num2str(ME.year.PM) ' Tn'])
disp([' '])
```

Annex 3. Make_emissions_map.m

```
clear all,clc,close all

%% MAKE AN EMISSION MAP
%This code will produce figures of the hourly consumption and emission
%rates for the route packages introduced.

%%% USER INPUT
ARX={'month7.mat','month5.mat'}; %load AIS route packages from
monthly_routes.m
dir_arx='in/';
nom='CASE E8 '; %Name of the output figure
LonMin=-5.5;LonMax=37.0;LatMin=30;LatMax=44.6;%Mediterranean %COORDINATES OF
THE PLOTTING AREA

%%%Ship engine and fuel data

EL=0.80;%Engine load (in unit percentage)
Pow_Ins=36560;%Engine Power(kW)
V_design=19.6;%Velocity design (knots)
SFOC=174; %Specific fuel compsuntion (gr/kWh).
SC=0.059; %Sulphur content of fuel (mass%) for Fuel Oil
CC=0.86; %Carbon content of fuel (mass %)
Engine_RPM=104; % Engine rpm

M_S=32.0655; %Molar mass of sulphur (gr/mol)
M_SO2=64.06436; % molar mass of sulphur dioxide g/mol (number of mols of
S=number of mols of SO2)
M_C=12.01; %Molar mass of carbon (gr/mol)
M_CO2=44.0886; %Molar mass of carbon dioxide (gr/mol) (number of mols of
C=number of mols of CO2)

%%PARTICULATE MATTER%

EF_EC=0.08; %Emission factor elementary carbon (gr/kWh)
EF_OC=0.2; % Emission factor for organic carbon (gr/kWh)
EF_ASH=0.06; %Emission factor for ash (gr/kWh)
OC_EL=1.024; %Part of organic carbon dependent of EL (dimensionless)

%%%%% END OF INPUT

%%%%
j=length(ARX);
if j>12
    disp('Please, only 12 files maximum.')
    return
end
if j<1
    disp('Please, enter at least a month file.')
    return
end

b=0;
for b=1:j
```

```
    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];



    a=0;
    for a=1:AIS.n

        rname = ['route',num2str(a)];
        AIS.Month.(rname);
        ROUTES.(mname).(rname)=AIS.Month.(rname);
        [m,n]=size(ROUTES.(mname).(rname));

        T=0.05;
        cte_k=(EL*Pow_Ins)/(V_design)^3;%Constant K (kW/kn^3)
        Pow_trans_h_AIS=cte_k*(ROUTES.(mname).(rname)(:,2)).^3;%hourly
transitient Power (kW)

%Pow_trans_AIS=sum(Pow_trans_h_AIS(1:end))/(length(Pow_trans_h_AIS));%Transit
ient Power
        Pow_trans_AIS=Pow_trans_h_AIS;

        %T=0.05;
        T=AIS.Month.(rname)(:,1);
        k=length(Pow_trans_AIS);
        for t=k:-1:2
            T(t)=T(t)-T(t-1);
        end

        FC=Pow_trans_AIS(:).*SFOC/.10^(-06);%tn/h


        n_SO2=(SFOC*SC)/M_S;% number of mols of sulphur dioxide
        Emi_fac_SO2=M_SO2*n_SO2; % SO2 Emission factor gr/kWh

        SO2=Pow_trans_AIS(:).*Emi_fac_SO2/.10^(-06); %gr

        %%% CO2
        n_CO2=(SFOC*CC)/M_C;% number of mols of carbon dioxide
        Emi_fac_CO2=M_CO2*n_CO2; % CO2 Emission factor gr/kWh

        CO2=Pow_trans_AIS(:).*Emi_fac_CO2/.10^(-06); %gr

        %%% NOX
        %Emi_fac_NOx=45*Engine_RPM^(-0.2); %NOx emission factor gr/kWh

        if Engine_RPM<130;
            Emi_fac_NOx=17;
        else
            if (130<=Engine_RPM)&&(Engine_RPM<=2000);
                Emi_fac_NOx=45*Engine_RPM^(-0.2);
            else
                if Engine_RPM>2000;
                    Emi_fac_NOx=9.8;
```

```
                end
            end

        end

        NOx=Pow_trans_AIS(:).*Emi_fac_NOx/.10^(-06);

        %%% PARTICULATE MATTER

        EF_SO4=0.312*SC; % Emission factor for SO4 (gr/kWh)
        EF_H2O=0.244*SC; % Emission factor H2O (gr/kWh)

        SFOC_REL=(0.445*EL^2)-(0.71*EL)+1.28; %(Specific fuel oil consumption
- Relative)

        Emi_fac_PM=SFOC_REL*(EF_SO4+EF_H2O+EF_OC*OC_EL+EF_EC+EF_ASH);
%Particulate matter emission factor (gr/kWh)

        PM=Pow_trans_AIS(:).*Emi_fac_PM/.10^(-06);  % Particulate matter
emitted in gr AIS route


MAP.(mname).(rname).FC=[FC,AIS.Month.(rname)(:,4),AIS.Month.(rname)(:,5)];

MAP.(mname).(rname).SO2=[SO2,AIS.Month.(rname)(:,4),AIS.Month.(rname)(:,5)];

MAP.(mname).(rname).CO2=[CO2,AIS.Month.(rname)(:,4),AIS.Month.(rname)(:,5)];

MAP.(mname).(rname).NOx=[NOx,AIS.Month.(rname)(:,4),AIS.Month.(rname)(:,5)];

MAP.(mname).(rname).PM=[PM,AIS.Month.(rname)(:,4),AIS.Month.(rname)(:,5)];

    end
end

load in/ldc_euro_i_mask;
lon(lon<LonMin)=NaN;
lon(lon>LonMax)=NaN;
lat(lat<LatMin)=NaN;
lat(lat>LatMax)=NaN;

%% Fuel consumption
plot(lon,lat,'k-','linewidth',1)
axis([LonMin LonMax LatMin LatMax]);
hold on

xlabel('Longitude'),ylabel('Latitude')
type=' Fuel Consumption (Tn/h)';
title(strcat(nom, type))

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];

    a=0;
```

```
    for a=1:AIS.n
        rname = ['route',num2str(a)];


scatter(MAP.(mname).(rname).FC(:,3),MAP.(mname).(rname).FC(:,2),25,MAP.(mname
).(rname).FC(:,1));

    end
end

colorbar,shading interp
colormap('bluewhitered')
caxis([0 8])

set(gcf,'PaperPositionMode','Auto')
nom2=['out/emissions/FC ' nom];
print ('-dpng','-r300',nom2)

close all

%% SO2

plot(lon,lat,'k-','linewidth',1)
axis([LonMin LonMax LatMin LatMax]);
hold on

xlabel('Longitude'),ylabel('Latitude')
type=' SO2 (Tn/h)';
title(strcat(nom, type))

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];

    a=0;
    for a=1:AIS.n
        rname = ['route',num2str(a)];


scatter(MAP.(mname).(rname).SO2(:,3),MAP.(mname).(rname).SO2(:,2),25,MAP.(mna
me).(rname).SO2(:,1));

    end
end

colorbar,shading interp
colormap('bluewhitered')
caxis([0 0.9])

set(gcf,'PaperPositionMode','Auto')
nom2=['out/emissions/SO2' nom];
```

```
print ('-dpng','-r300',nom2)

close all

%% CO2

plot(lon,lat,'k-','linewidth',1)
axis([LonMin LonMax LatMin LatMax]);
hold on

xlabel('Longitude'),ylabel('Latitude')
type=' CO2 (Tn/h)';
title(strcat(nom, type))

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];

    a=0;
    for a=1:AIS.n
        rname = ['route',num2str(a)];


scatter(MAP.(mname).(rname).CO2(:,3),MAP.(mname).(rname).CO2(:,2),25,MAP.(mna
me).(rname).CO2(:,1));

    end
end

colorbar,shading interp
colormap('bluewhitered')
caxis([0 25])

set(gcf,'PaperPositionMode','Auto')
nom2=['out/emissions/CO2' nom];
print ('-dpng','-r300',nom2)

close all

%% NOx

plot(lon,lat,'k-','linewidth',1)
axis([LonMin LonMax LatMin LatMax]);
hold on

xlabel('Longitude'),ylabel('Latitude')
type=' NOx (Tn/h)';
title(strcat(nom, type))

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];
```

```
    a=0;
    for a=1:AIS.n
        rname = ['route',num2str(a)];

scatter(MAP.(mname).(rname).NOx(:,3),MAP.(mname).(rname).NOx(:,2),25,MAP.(mna
me).(rname).NOx(:,1));

    end
end

colorbar,shading interp
colormap('bluewhitered')
caxis([0 0.8])

set(gcf,'PaperPositionMode','Auto')
nom2=['out/emissions/NOx' nom];
print ('-dpng','-r300',nom2)

close all

%% PM

plot(lon,lat,'k-','linewidth',1)
axis([LonMin LonMax LatMin LatMax]);
hold on

xlabel('Longitude'),ylabel('Latitude')
type=' Particulate Matter (Tn/h)';
title(strcat(nom, type))

b=0;
for b=1:j

    filename=[dir_arx ARX{b}];
    AIS=load(filename);
    mname = ['month',num2str(b)];

    a=0;
    for a=1:AIS.n
        rname = ['route',num2str(a)];

scatter(MAP.(mname).(rname).PM(:,3),MAP.(mname).(rname).PM(:,2),25,MAP.(mname
).(rname).PM(:,1));

    end
end

colorbar,shading interp
colormap('bluewhitered')
caxis([0 0.017])
```

```
set(gcf,'PaperPositionMode','Auto')
nom2=['out/emissions/PM' nom];
print ('-dpng','-r300',nom2)

close all
```